GYPSUM, ANHYDRITE AND PLASTER OF PARIS AS SOIL STABILIZERS

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CHAPTER I

INTRODUCTION

General

The highway engineer, in certain areas of the United States, is faced with the growing problem of building bigger and better highways with existing materials found near the proposed road site. He is continually searching for new supplies of gravel and crushed rock that are suitable and economical. These supplies are nearly exhausted, and the ever rising cost of construction forces the engineer to use locally available soil materials in increasing quantities.[1]

Certain types of soil materials are very detrimental to good subgrade or base construction. These soils have very small particles which, by their size and mineralogical composition, impart properties of plasticity, low strength, shrinkage, and swelling, and inhibit drainage under certain conditions. For example, the plastic red clays, of the Permian Age, found in abundant supply in Oklahoma are of this type. These clays are usually the villains that produce failures in existing highways in Oklahoma. When the engineer encounters these plastic clay deposits, he either replaces the clay material with a select soil material or builds a sufficiently thick base on it. The supplies of crushed gravel, rock and select soils used for bases and subgrades are becoming

scarce in Oklahoma. Therefore, the engineer is in need of a way to alter the existing clay to make it usable as a road construction material.

Purpose of Investigation

There occur, in the western counties of Oklahoma, large deposits of gypsum and anhydrite. The gypsum is processed and used in a number of different products. The anhydrite is practically useless commercially.

The idea of mixing either gypsum, anhydrite or plaster of Paris, a product of gypsum, with the clay and producing a good road construction material has occurred to the engineer. These supplies of materials are convenient, relatively economical and if proved to be beneficial, would be a lasting source of building material for future projects.

A review of past work done in the field of altering a soil with a chemical, has produced a great amount of material.[2-5] These works deal mostly with using portland cement, bituminous products, lime or organic chemicals. But the investigations of the use of gypsum or one of its related compounds are practically nonexistent.[6-9]

The Oklahoma State Highway Department and the Bureau of Public Roads, through the Oklahoma State University, sponsored a project to examine the feasibility of using gypsum or any of its related compounds as a soil stabilizer. It is hoped that the findings of this investigation will prove to be fruitful and provide the highway engineer with a new road construction material.

Scope of Investigation

The object of the investigation was to determine if gypsum, anhydrite or plaster of Paris have any merits as a soil stabilizer. The area of study was to include plasticity tests to determine the change in plasticity, unconfined compression tests to determine changes in strength, swelling tests to examine the changes in potential swelling ability and triaxial tests to find changes in the shearing strength parameters of the soil. These tests would give an overall picture of how the added materials affect the soil. Also these tests are a good measure of the properties that need to be altered, such as workability, swelling ability, and shear strength. By far the greatest amount of testing was done through the unconfined compression test.

The major part of the investigation deals with the study of gypsum, but it was felt, after some testing, that anhydrite or plaster of Paris would have better chances. Therefore, later in the investigation equal importance was placed on all three of the materials.

It is believed that either gypsum, anhydrite or plaster of Paris, used in the right manner would have a beneficial effect upon soil used as a road construction material.

CHAPTER II

SOIL STABILIZATION

Methods

In highway construction, the term stabilization refers to methods of treatment that improve the soil by increasing the strength and decreasing the ability of the soil to undergo volumetric changes. There are four basic classifications of stabilization used in highway construction. They are mechanical, physical, chemical and physico-chemical stabilization.

Mechanical stabilization consists of manipulation and compaction, usually with the use of water and sometimes with salt solutions that are not entirely alien to the soil. This method changes the physical properties but does not render them fundamentally different.

Physical stabilization is the preparation of graded soil mixtures by adding to coarse size material a fine soil constituent. The two materials do not lose their physical properties, but can be reclaimed by physical methods.

Chemical stabilization is accomplished by the addition of materials which, because of their own chemical character and that of the soil system, react and form new systems from which the original components cannot be reclaimed by physical and mechanical methods.

Physicochemical stabilization is a combination of physical and surface-chemical factors which cannot be cleanly separated, while the relative importance of each of these factors may vary.[11]

Mechanical and physical stabilization are widely used in the road construction industry. Their importance cannot be overemphasized, but the method of stabilization considered in this investigation is thought to be chemical or physicochemical. Before a study of chemical and physicochemical stabilization can be accomplished, a basic understanding of the fundamental behavior of clay minerals is needed.

Fundamental Concepts of Clay

Forces

A soil system or any coherent mass is tied together by three-dimensional forces. Those forces are of two types, the first is chemical or primary, and the seond is physical or secondary. Three chemical forces that would help describe soil stabilization are the ionic bond, the covalent bond and the hydrogen bond. The ionic bond is a transfer of electrons from one atom to another to form ions, charged particles, which are held together by electrostatic forces. The covalent bond is the sharing of one electron by two atoms. The hydrogen bond is the attraction of two negatively charged (anions) atoms by the positively charged (cation) hydrogen ion.

Physical forces are those that exist between molecules (groups of atoms united by chemical forces) and discrete aggregates and are essentially surface forces. There are two types of physical forces that would be of interest in soil stabilization, they are the Van Der Waal

forces and polar forces. Van Der Waal forces are those that exist between molecules that have no localized electrical charge whereas polar forces exist at a localized electric charge.

Physical forces are weaker than chemical forces and can be broken by physical methods. However, on removal of the physical disturbance, the original bond reverts to an essentially unaltered form. The chemical bond requires far more energy to break it, but once broken it does not reform spontaneously. Therefore, stabilization is affected by altering the secondary forces or by adding a material that bonds through its own primary or secondary forces.[12]

Structure

After the turn of the century, students of clay materials suggested that clay was composed of very small particles of a limited number of crystalline minerals. This was later substantiated by research.

The common clay minerals, as the crystalline minerals were called, are hydrous aluminum silicates. The hydrous aluminum silicate minerals are composed of two fundamental building blocks. The first is a tetrahedral silica unit composed of four oxygen ions enclosing a silicon ion. The bases of the tetrahedral silica units are bonded together with other silica units by ionic and covalent bonds, forming sheet layers of tetrahedrons with their apex's in one direction and their bases forming a plane. Each silica unit has a sum total charge of -1.

Octahedral hydrous aluminum oxide is the second fundamental building block which is usually called gibbsite. It consists of six hydroxyl ions enclosing an aluminum ion with a total charge of +1.

Each unit is bonded together in a sheet structure having each hydroxyl ion common to 3 octrahedral units. Sometimes iron or magnesium may substitute for the aluminum in the octrahedral unit by isomorphous substitution.

The sheet structures of the two fundamental building blocks are bonded together in different ways to form the different clay minerals. The apex's of the silica sheet are intergrown with the hydroxyl ions of the gibbsite sheet, forming a two layer sheet. If there is an excess of silica, a silica sheet is bonded to the other side of the gibbsite sheet forming two silica sheets with a gibbsite sheet in between. This gives a more negative charge than the elemental gibbsite-silica sheet because of the extra silica sheet.

Kaolinite, a clay mineral, is formed with alternating sheets of silica and gibbsite. It is fundamentally a two layer structure of silica and gibbsite bonded together by hydrogen bonds to succeeding silica and gibbsite layers. Kaolinite is formed in nature by the chemical weathering of feldspar and other aluminum bearing rocks.

Minerals of the montmorillonite group consist of a gibbsite sheet being enclosed, sandwichlike, between two sheets of silica. This type of sheet structure produces an excess of negative charges. The negatively charged surfaces of the sheet structure may be separated by dipolar water molecules oriented with their positive charges toward the negatively charged surface of the sheet. The distance between sheets depends on the amount of water present. Also cations of different elements may tie the elemental sheets of montmorillonite together.

Illite, the last of the clay minerals to be discussed, is similar to montmorillonite except that elemental sheets are bonded together by potassium or other ions rather than by water. The potassium bond is stronger than the water bond in montmorillonite and the tendency of forming ultimate platelets in illite is less than for montmorillonite.[13]

Ion Exchange

Clay minerals have the ability to sorb or replace cations or anions. This reaction takes place around the silica-alumina sheet unit and does not affect the sheets structurally. Many properties of the clay minerals are related to and are affected by the exchangable ion it contains. For example, the liquid limit and the permeability are greatly affected by the type of cation on the clay particle.

There are three types of mechanisms which influence the cation exchange capacity of clay minerals. One is the broken bonds which exist at the edges of the silica-alumina sheets. These broken bonds result in unbalanced charges at the edges of the sheet and the adsorbed ions satisfy this unbalanced charge. In kaolinite and illite this is a major cause of cation exchange. Another method of cation exchange is through substitution, within the lattice structure, of ions of lower valence, particularly magnesium, for trivalent aluminum in the octrahedral sheet. Exchangable cations resulting from lattice substitution are to be found mostly on the basal cleavage surfaces of the layer clay minerals. In montmorillonite, substitution within the lattice is the major method of cation exchange. The last method is by the exchange of a cation with the hydrogen of exposed hydroxyls. This is important in the case of

kaolinite. The property of ion exchange capacity is measured in terms of milliequivalents per 100 grams and is determined at pH 7 or neutrality.

The kind and the amount of cation exchanged on a clay particle is dependent on many different variables such as the nature and concentration of the clay minerals, the nature and concentration of the ion and many other factors.

Clay-Water Relationships

The properties of clay are greatly dependent on the amount and the form of water present. There are four basic classifications in which water may exist in a clay mass.

Structural water is essentially not water, but is the hydroxyl groups which are integral parts of the solid crystal lattice. This water can only be removed by high temperature breakdown of the crystal structure.

Adsorbed water is present in thin (1-10 molecules) layers on both the exterior and interior (for expanding lattice materials) surfaces. This water is practically immobile because of the extremely large forces holding the water molecules.

Solvation water is present in thin layers around the individual solid particles. The viscosity of the water varies from that of thick molasses, close to the particle, to that of ordinary water at a distance of a few hundred angstroms.

Pore water has all the physical and chemical properties of ordinary water. Such water is displaced by normal hydrodynamic means unless it

is present in sealed off pores; or unless capillary forces, holding the water, are greater than available hydrodynamic forces.[14]

Soil Stabilization Reactions

Soil stabilization reactions can be classed broadly according to whether the reaction is of a physical or a chemical nature. The two overlap with uses of certain stabilizers, and it is difficult to classify the reaction as distinctly physical or chemical.

Physical Reaction

Usually the stabilizing agent is essentially formed before it is added to the soil and requires an alteration in its physical condition before it becomes effective. An example of this is the addition of a bituminous material, either as an emulsion or as a cutback asphalt, with the subsequent driving off of volatiles producing a solid. The stabilization occurs with the phase change from liquid to solid of the bitumen and the soil acts only as an aggregate. Again with portland cement, stabilization occurs with the hydration of the cement. But in this case the soil may also play a role in the reaction, which is chemical in nature.

Chemical Reaction

This differs from physical reaction in that a new material is formed, with different properties from the materials originally introduced, by a chemical reaction and not just a phase change. Out of the many chemical reactions, four might be considered for stabilization.

They are cation exchange, pozzolanic reaction, precipitation and polymerization.

Cation exchange and the crowding of additional cations onto the clay, are processes acting to change the electrical charge density around the clay particles. Clay particles then become electrically attracted to one another, causing flocculation or aggregation. The aggregated clay behaves like a silt, which has low plasticity or cohesion. This happens when a cation such as calcium, derived from lime or from portland cement, is introduced.

Pozzolanic reaction is the term used to describe lime reacting at ordinary temperature with any natural or artificial siliceous or aluminous material in the presence of water to form stable, insoluble compounds possessing cementing properties.

Precipitation is the reaction of compounds in solution to form a new compound which is insoluable and therefore precipitates out of solution. Some of these precipitates possess characteristics which make them suitable as stabilizing agents.

Polymerization is the growing or forming of large molecules or compounds by the reaction of simple compounds. This reaction best explains stabilization ability of some organic chemicals.

CHAPTER III

MATERIALS USED FOR THE INVESTIGATION

Admixtures

Initially, gypsum was to be the only admixture to be tested. If there was to be a stabilizing effect, either by ion exchange or a cementing action, then gypsum would seem to be the logical choice. But after some laboratory testing, it was decided that it might be profitable also to experiment with materials similar to gypsum. Anhydrite is found bedded with gypsum, and plaster of Paris is a product of gypsum. Both can be produced at a reasonable cost and both differ from gypsum only in the chemically combined water. Also, a check was needed to compare the results of the stabilization; and since a great amount of soil stabilization has been accomplished by the use of lime, specimens containing lime were tested. A more detailed discussion of the admixtures used is discussed below.

Gypsum

The term gypsum is a mineral name and a rock name for hydrous calcium sulphate, $CaSO_4 + 2H_2O$. Gypsum belongs to a rock family known as evaporites, which are formed by the partial or complete evaporation of marine brine. It occurs in a different variety of forms, as satin spar, a fibrous form with a silky luster; selenite, a transparent

cleavable form; and alabaster, finely crystalline and massive. The gypsum used in industry is a compact massive finely crystalline to granular rock. It is white when pure, but may be pink, gray, bluish-gray, or yellow owing to impurities.

The greatest use for gypsum depends on a unique property. When gypsum is heated to a moderate temperature, around 70°C, it loses three-fourths of the chemically held water. The resulting hemihydrate (calcined gypsum or plaster of Paris) may be mixed with water and, on setting, forms a dense rocklike mass of intergrown needlelike crystals of reformed gypsum. This property has been known to man for centuries. The Egyptians used such plasters on the walls of tombs, and every civilization since ancient Egypt has utilized it.

Today, more than 95 per cent of the gypsum produced is calcined; and nearly all of the product is used in making gypsum plaster, lath and wallboard.[15]

In agriculture, finely ground gypsum is added to the soil as a conditioner and fertilizer ("land plaster").

Oklahoma occupies a central position in the belt of country which carries extensive gypsum deposits from the northern part of Kansas into central Texas. The amount of gypsum appears to be inexhaustible. Also the deposits are readily accessible, mostly flat lying, or nearly so, and at or near the surface. The rock is extracted in bulk by conventional methods.

The structure of gypsum is monoclinic and has a layer-lattice. Each layer contains sulfate radicles $(SO_4)^{-2}$ linked to calcium ions. A calcium ion is surrounded by eight units, six of these are oxygen ions,

of which there are two from each of three sulfate groups, and the other two coordinating groups are water molecules. The linking between layers is through these water molecules which have weak bonds and give rise to cleavage along these planes.

The gypsum used in the investigation was obtained from the United States Gypsum Company at Southard, Oklahoma. It has a specific gravity of around 2.32 and a hardness of 2 on Mohs scale. The gypsum was passed through a number 10 sieve and had a coefficient of uniformity of 5. A grain size distribution curve for gypsum is shown on Figure 1.

Anhydrite

The mineral anhydrite is closely related to gypsum, as it is anhydrous calcium sulphate, $CaSO_4$. It is similar in appearance to gypsum but is somewhat harder and heavier. Anhydrite occurs interbedded or intercrystallized with gypsum. Some geologists, who have studied commercial deposits in the field, believe that the primary precipitate, from the ancient oceans, was anhydrite; and gypsum resulted from the hydration of anhydrite in the zone of weathering.[15]

At the present time, only a limited quantity of anhydrite is utilized commercially. It is used as a retarder in the manufacture of portland cement. But the greater majority is considered as a contaminant in gypsum deposits.

Anhydrite is orthorhombic in structure. It contains a calcium ion linked to eight oxygen ions, not all of which are at the same distance from it.

The anhydrite was also obtained from the United States Gypsum Company, and it has a specific gravity of around 2.9 and a hardness of 3. The material was passed through a number 10 sieve, as was the gypsum; and it was assumed to have approximately the same grain size distribution.

Plaster of Paris

When pure gypsum is heated to a temperature of more than 70°C, a certain definite portion of the chemically-held water will be driven off; and the gypsum, thus partially dehydrated, will be plaster of Paris, $2CaSO_4 + H_2O$. Plaster of Paris will harden or set very rapidly when mixed with water, readsorbing sufficient water to regain its original composition of $CaSO_4 + 2H_2O$. If, however, the crude gypsum carried a large percentage of impurities, or if certain materials are added after burning the gypsum, the product will set much more slowly. Such slow setting plasters are of value in structural work and are called by the misleading term "cement plasters".

Plaster of Paris has a structure akin to zeolites in that water may be removed without destroying the crystal lattice. On heating to about 300°C it forms soluble anhydrite, $CaSO_4$, which has the same structure and reacts in the same way with water as the original plaster of Paris. Heating to a higher temperature will alter the structure and normal anhydrite is formed.

"Red Top Plaster", a commercial name for "cement plaster" was used because of its slow setting property. An ideal setting time of

8 hours was decided upon, and this was achieved by accelerating the set of the "cement plaster" with 5 per cent gypsum. This plaster has a specific gravity of 2.5 and a hardness of 2.

Lime

Lime or "quicklime" (CaO) is obtained by burning pure limestone at a very high temperature of 1000°C - 1100°C. The quicklime has a strong affinity for carbon dioxide and tends to combine with water, with the evolution of heat. For this reason, hydrated lime (CaOH) was used, rather than the CaO. The hydrated lime was obtained from a commercial laboratory. It has a specific gravity of 2.1.

Clay Materials

The clay materials chosen for the investigation were Permian red clay, bentonite and kaolinite. The first was chosen for obvious reasons, since this is one clay that gives troubles to the highway engineer. The second was chosen because it contains a large amount of montmorillonite, a very plastic clay mineral with an expanding lattice and a large base exchange capacity. Kaolinite was chosen because it is low in plasticity, does not swell with the addition of water and has a low base exchange capacity. It was felt that these clay materials would best describe the possible range of clay materials that would be encountered in the field.

Permian Red Clay

Permian red clay is the predominant clay soil in Oklahoma and the Southwest. Some of these clays contain sand, some contain silt, and

others contain practically no sand or silt. The sandy clays, when dry, have the appearance of sandstone; and the clays that contain no sand or silt, when dry, look like shale. All of the Permain clays have been overconsolidated and, near the surface, have been through countless numbers of cycles of drying and saturation. Permian clays contain approximately 40 per cent montmorillonite, 30 per cent to 35 per cent illite, and 25 per cent to 30 per cent unidentified material. The unidentified material is probably quartz, kaolinite and iron oxide. The liquid limit varies from over 100 per cent for clays containing considerable montmorillonite to about 35 per cent for clays containing considerable sand and silt. However, on the average the liquid limit is around 50 per cent and the plastic limit is about 15 per cent.

For this investigation, Permian clay was obtained from an average depth of 2-5 feet in the general vicinity of the Oklahoma State University campus. The samples were air dried, pulverized and passed through a number 10 sieve. A grain size distribution curve is shown in Figure 2. Also the liquid limit, plastic limit and base exchange capacity of the Permian red clay are shown in Table I.

Bentonite

Bentonite is a clay material composed chiefly of the clay mineral montmorillonite. It is formed by the chemical alteration of volcanic tuff or ash.

Commercially, bentonite from Wyoming is used as a drilling mud because of its ability to absorb a large quantity of water. Bentonite is found in other states, but only the bentonite from Wyoming carrying

Na as the exchangeable ion will mix with water producing pronounced swelling.[15]

Some of the properties of Na bentonite are listed in Table I.

Kaolinite

Kaolinite is a clay mineral and is a term sometimes used to mean Kaolin, a clay material composed chiefly of kaolinite. Kaolin is used in the manufacture of ceramics and is found in the coastal plain of Georgia and South Carolina. Kaolin or kaolinite properties are listed in Table I.

CHAPTER IV

LABORATORY PROCEDURE AND TECHNIQUE

Proportioning of Materials

The proportioning of soil and stabilizer was accomplished on an air-dried weight basis. As an example, 200 grams of admixture and 200 grams of soil would give a 50 per cent admixture content. The batching was done on a triple beam balance with an accuracy to the nearest tenth of a gram. The materials were then thoroughly mixed to assure uniformity.

Moisture Content

As discussed in Chapter II, the amount of moisture a soil contains greatly influences the condition of the soil. Therefore, accurate control of the moisture content is important to achieve consistency in the testing. Initial moisture contents of all the materials were determined by oven drying the materials at 105°C and by dividing the weight of the water evaporated by the resulting dry weight of the material. Problems arose when moisture content determinations were attempted on mixtures containing gypsum. As stated in Chapter III, gypsum loses three-fourths of its chemically-held water when heated above 70°C. When moisture determinations by normal procedures were attempted on mixtures containing

gypsum, water of crystallization from the gypsum was driven off, thereby giving a false representation of the moisture content. Thus, all moisture content determinations of mixtures containing gypsum were made by drying at 65°C.

Compaction of soil specimens is also immensely dependent upon the amount of moisture the soil contains. For a given compactive effort, a soil will obtain its maximum density at a particular moisture content which is called the optimum moisture content. Figure 3 shows the optimum moisture content for the different clay materials, with varying percentages of admixtures.

Compaction

To the soil material and stabilizing agent that was to be compacted, the prescribed amount of distilled water was added, as determined from the optimum moisture content curves, and this was thoroughly mixed in an electric mixer. After mixing, the soil was covered to retard loss of moisture during compaction; but some moisture was lost. The samples were compacted using the Harvard miniature compaction apparatus. The compaction cylinder is 2.8 inches in height and 1.28 inches in diameter for the unconfined compressive specimens and 1.4 inches in diameter for the triaxial specimens. The compactive effort is supplied by a hand-operated spring-loaded device that supplies a 20 pound pressure through a 0.375 inch diameter piston. Densities approximately the same as the standard procter density were obtained by using three lifts with twenty five blows per lift. If the soil was exceptionally wet, six lifts were used and the given pressure reduced to 10 pounds. Standard procter

densities were run on some of the specimens to check the validity of the procedure using the Harvard miniature apparatus.

Storage

After compaction, the specimens were trimmed off flush and extruded from the cylinder. The samples were then wrapped in aluminum foil and coated with a wax covering. Specimens containing lime had a tendency to combine with the aluminum foil. Polyethylene plastic was used instead of the foil when wrapping lime stabilized specimens. Labels were placed on the specimens, and they were then stored in a humid room. A humidity of around 70 per cent was maintained in the humid room to reduce evaporative losses through the wax coating.

Plasticity Test

The plasticity of a soil mixture is usually measured by performing the Atterberg limits tests. Atterberg, a Swedish agriculturist, divided the cohesive range at which a soil can exist, from a solid to a liquid state, by five arbitrary limits. The two limits most often used in soil mechanics are the liquid and plastic limits. The liquid limit is the water content at the lower limit of viscous flow above which the soil and water flow as a liquid and below which the mixture is plastic. The plastic limit is the water content at which the soil will start to crumble when rolled into a thread. The Casagrande liquid limit device and grooving tool were used to determine the liquid limit.

Unconfined Compression Test

The unconfined compression test is the simplest test used to determine the strength of a cohesive soil, and may be used also in studies of stress-deformation relationships. The apparatus used for the unconfined compression test is an electrical, motor-driven Karol Warner testing machine. The motor speed is controlled by a variac having a forward and reverse motion. The rate of strain of the specimen was controlled by the speed of the motor, and it was set to produce failure of the specimen in about five minutes. No attempt was made to prevent loss of moisture during the testing. After testing, the specimens were examined as to the mode of failure; and then they were used to determine the actual moisture content at the time of testing.

The unconfined compression test machine is pictured in Plate I.

Triaxial Test

The triaxial test is used to measure the shear strength of a soil in conditions that approximately parallel that of a soil which exists in the field at different depths. Triaxial equipment is specially built so that lateral pressure may be applied to the soil specimens.

The soil sample was encased in a thin rubber membrane, placed in a closed lucite cylinder and subjected to a fluid pressure. Facilities for applying various drainage conditions are provided at the ends of the sample, so that actual drainage conditions in the ground may be simulated during testing. Ambient pressure was applied to the specimens, and they were allowed to consolidate for two days. Upon

completion of consolidation, the specimens were loaded to failure. Moisture content determinations were made after the testing. The triaxial equipment with its loading frame is shown in Plate II.

Swell Test

The swelling equipment utilized is shown in Plate III. These are PVC (potential volume change) meters designed by T. W. Lambe of Massachusetts Institute of Technology.[16] These meters measure the ability of soil to exert a swelling pressure when water is applied. Soil samples were compacted using a hammer similar to the Standard Procter hammer in a ring 2.75 inches in diameter and 0.625 inches in height. A loading ring was used to measure the resulting pressure when water was applied. Moisture contents were taken before and after testing.

CHAPTER V

DISCUSSION OF TEST RESULTS

Plasticity Tests

Only the plasticity of gypsum and Permian clay combinations was studied in these investigations. It was felt that gypsum would sufficiently show how the family of admixtures--gypsum, anhydrite and plaster--would affect the plastic properties of the clay.

The effect of gypsum content, in percentages varying from 0-60 per cent, on the plasticity of Permian clay is shown in Figure 4. The problem of obtaining incorrect moisture content resulted when the mixtures were dried at too high a temperature. A mathematical correlation factor was applied to the results of the limit tests dried at 105°C to correlate with those dried at 65°C. This was accomplished by determining the amount of water of crystallization removed from the gypsum by a drying temperature of 105°C, expressed as per cent by weight. The amount of water removed from the gypsum in a given specimen was calculated and expressed as a percentage of the dry weight of the mixture. This was subtracted from the indicated limit to obtain the true limit of the mixture.

The plastic limit decreased slightly, whereas the liquid limit decreased sharply for increasing gypsum content. A decrease of nearly 50 per cent was exhibited for the liquid limit, the value varying from

40 for 0 per cent gypsum to 20 for 60 per cent gypsum mixtures. The plastic index, which is the liquid limit minus the plastic limit, decreased in accordance with the liquid limit because the plastic limit remained nearly constant. The effect of gypsum on the plasticity of the mixture is noticeable in the actual handling of the material. Because of the plasticity of the Permian clay, it is hard to get a uniform dispersion of the moisture through the soil. The clay balls up and, with increasing water content, becomes sticky and unmanageable. However, with increasing gypsum content, the workability improves markedly. Essentially, the effect is that of causing the cohesive clay to more nearly resemble a cohesionless soil. This improved workability favors the use of gypsum as a stabilizer.

Unconfined Compression Test

Gypsum-Permian Clay

Three variables were considered in testing the effect of gypsum on the strength of Permian clay. By varying the gypsum content, length of curing time and moisture content, an overall perspective of a stabilizing effect, if any, could be ascertained.

Effects of four separate curing times are shown in Figures 5 through 8, and each will be discussed later.

Three different moisture contents were used in testing each gypsum content. The optimum moisture content, 2 per cent above optimum and 2 per cent below optimum were employed in arriving at the amount of water to be used in compacting the specimens. Referring to Figure 5, the three straight lines indicate the water content at compaction for

the various mixtures. The plotted points indicate the moisture content at testing. Since the strength of a compacted clay is directly dependent on the moisture content, it was surmised that, if a clay sample were compacted and tested at its optimum moisture content, it would have a certain definite strength. If the sample were compacted at optimum and found to have a higher moisture content at testing, it would then be logical to say that the specimen is in a weaker condition than if it had been tested at optimum moisture content. In like manner, if the mositure content at testing were lower than at compaction, then the strength of the sample would be higher than it would have been had the moisture content remained the same. This is the reasoning governing the relationships between the plotted points and the curves which were drawn for strength versus the gypsum content. To further explain this relationship, three amounts of water content-- 2 per cent above optimum, 2 per cent below optimum and optimum--were used in compacting the mix having 10 per cent gypsum content. The specimens were tested for strength, and moisture content determinations were made following the testing. The data from the strength test and the moisture determinations were plotted, the moisture content at testing was compared to the moisture content at compaction. At 2 per cent below optimum, it was found that both moisture contents coincided; therefore, the curve of strength versus gypsum at low moisture content passes through the point found at testing. The strength curves for optimum and 2 per cent above optimum were drawn above the plotted points because moisture content of these specimens at testing was above their intended moisture content at compaction. This method of positioning the curves in

relationship to the plotted points has been used throughout these studies unless otherwise noted.

For one-day curing time, shown on Figure 5, the addition of gypsum decreases the unconfined compression strength of the Permian clay. This decrease in strength occurs in the succeeding curing times of 7 days, 28 days and 6 months, as shown in Figures 6, 7 and 8 respectively. In Figures 6, 7 and 8, the curve labeled "L" generally decreases slightly, while the curves labeled "M" and "H", which parallel each other fairly consistently, increase at 50 per cent gypsum, for some unexplainable reason. But the general trend for all curing times and gypsum contents revealed a decrease in the strength of the Permian clay. In Figure 9, the relationship between curing time, up to 28 days, and strength of Permian clay and gypsum compacted at optimum is shown; the increase is slight. Figure 10 shows the effect of the total 6 months curing time on the strength of gypsum and Permian clay combinations.

It was hoped that gypsum would give an increase in strength to the Permian clay, either through base exchange or a cementation action. But, as shown by the curves, there was not an increase in strength. It could be surmised that a cementation action or a complete base exchange reaction did not occur.

Gypsum is slightly soluble in water, which means that gypsum dissociates into a calcium ion and a sulfate ion. It seems probable that gypsum would also dissociate in a gypsum-clay mixture in which water has been added for compaction. Perhaps, if the individual particle size of the gypsum is too large, a sufficient quantity of calcium ions would not be available for a base exchange. It followed from this line

of thinking that perhaps the gypsum was not in a small enough particle size to release enough calcium ions to saturate completely the clay particle surfaces. The gypsum used for the strength determinations shown in Figures 5-8 was that passing the number 10 sieve. It was decided to reduce further the average size of the gypsum particles by screening the gypsum through a number 100 sieve.

Specimens containing the gypsum passing the number 100 sieve were compacted at the optimum moisture content. The results of the testing are displayed in Figure 11. The same procedure of adjusting the strength curve by referring to the moisture contents is used. It is obvious that there is a marked increase in strength, especially for a curing period of 180 days. The curves depicting curing periods of 1 and 7 days show a slight increase in strength, and the curing period of 28 days shows a definite trend of increasing strength with length of cure. For a curing period of 6 months, there is a 400 per cent increase in strength, ranging from an unconfined strength of 2 tons per square foot at 0 per cent gypsum to a strength of around 8 tons per square foot at 30 per cent gypsum. Insufficient time did not permit the testing of 40 per cent and 50 per cent gypsum content, at 6 months curing time. In Figure 11 it is shown that specimens cured for 6 months have greatly increased strengths. However, it may be noted that these samples were considerably drier at testing than at compaction. This probably contributes to the strength, but it seems unlikely that the increased strengths are solely due to the decrease in moisture. Evidently, a base exchange or a cementitious action takes place with increasing time of cure. Apparently, if gypsum particles are small enough, and if

sufficient curing time is permitted, a rather high strength may be obtained. Figure 12 demonstrates the effect of curing time on the strength of Permian clay and gypsum passing the number 100 sieve. This curve reveals that with a 30 per cent gypsum content, a 750 per cent increase in strength will occur in 6 months time. The discrepancy between the maximum strengths obtained in Figures 11 and 12 is because there was no adjustment for moisture content differences in Figure 12. The "w's" shown on Figure 12 indicate water contents at testing, and they may be compared with the water contents at compaction in Figure 3.

Gypsum-Bentonite

Combinations of gypsum passing the number 10 sieve and bentonite were compacted using the optimum moisture content. The unconfined compression strength of bentonite, at its optimum moisture content, is approximately the same as Permian red clay at its optimum. With increasing gypsum content--up to 10 percent, there is a moderate increase in strength. As the gypsum content is further increased, the strength drops off at first and then begins to rise again. This effect is shown in Figure 13. As may be seen from the curves, there is no phenomenal increase in strength. There is an indication, however, that with increasing lengths of curing time, there is an increase in strength. Samples were compacted and tested after a 180 day curing time; but it was obvious, when unwrapping the wax coating from the specimens, that the specimens were much drier than when compacted.

Bentonite was chosen as a different clay soil to test the merits of gypsum as a stabilizer. Bentonite is composed chiefly of the clay

mineral montmorillonite, which has a large base exchange capacity and has extremely small particle sizes. Because of these properties, one would expect a base exchange reaction to occur. If base exchange does occur, it is quite possible that the strength of the mixtures would be improved. However, as shown by the curves, the increase in strength is minor.

Gypsum-Kaolinite

Kaolinite was used to provide a clay mineral of vastly different properties than those of bentonite. The plasticity is low, the base exchange capacity is low and it has a slight activity. Figure 14 expresses the effect of gypsum passing the number 10 sieve on the strength of kaolinite. There is a noticeable increase in strength for all curing periods with percentages greater than 10 per cent. Also there is an increase in strength for each succeeding curing period. Adjustments for moisture contents were not attempted for the initial 3 curing periods, but a rather conservative adjustment was made for the 180 day curing period.

For a soil with considerable amounts of kaolinite, an increase in strength may be obtained with the use of gypsum. Major drawbacks are the large quantity of gypsum needed and the long curing period required to produce significant effects.

Anhydrite-Permian Clay

Anhydrite, as discussed in Chapter III, is a close relative of gypsum. The material is chiefly discarded as an unwanted rock in the open-pit mining of gypsum. If anhydrite could be used as a stabilizer

in road construction, an otherwise wasted natural resource could be put to use.

Combinations of Permian clay and anhydrite passing the number 10 sieve were compacted using the optimum moisture content. As can be seen from Figure 15, there is no apparent increase in strength for 1 and 7 day curing periods, while there is a slight increase in strength after 28 days. A very large increase in strength is achieved after 6 months curing time. The optimum anhydrite content appears to be between 25-40 per cent, with an increase of nearly 600 per cent in strength at 180 days curing time. The curve for 180 day curing time is the only one adjusted for moisture content differences.

Actually, a substantial increase in strength may be obtained at 10 per cent anhydrite content with sufficient curing time. As shown in Figure 15, an increase of around 300 per cent is indicated for 10 per cent anhydrite mixes after curing for 180 days. Figure 16 is a curve showing the relationship between curing time and anhydrite content. It can be seen that an optimum anhydrite content is reached between 25 and 40 per cent. After testing the specimens cured for 180 days for strength, an examination was made of the anhydrite particles. They appeared to have undergone a change in their physical state. In appearance, these particles bore a close resemblance to gypsum. The surfaces of the particles could be scratched with the fingernail, and the particle size could be further reduced in size with the fingernail. Anhydrite is a fairly hard rock, and it cannot be scratched readily with the fingernail. Evidently some sort of chemical reaction takes place between the Permian clay and the anhydrite to produce a substance similar to gypsum.

How this could give an increase in strength to the Permian clay is not known.

Additional samples were compacted using anhydrite passing the number 200 sieve to see if the reaction time could be speeded up. This series of tests has not yet been completed, and none of the data are presented here. However, the 1, 7 and 28 day tests showed a slight increase in strength compared to the specimens compacted using anhydrite passing the number 10 sieve.

Evidently, anhydrite has the ability to impart added strength to Permian clay. More testing would have to be carried out for plasticity, activity, and weathering ability before anhydrite could be definitely recommended as a stabilizer of soil.

Plaster-Permian Clay

Gypsum plaster was the last of the gypsum family investigated as a stabilizer. Samples containing Permian clay and plaster were compacted at their approximate optimum moisture content and cured for varying periods of time. The results of unconfined compression tests are shown in Figure 17. There was no detectable difference in strength for 1, 7 and 28 day curing times. It was expected that there would not be any substantial increase in strength after 8 hours curing time. It is known that the plaster will set up, forming a matrix of intergrown crystals which will give strength to the clay-plaster combination. This was considered to be the only mechanism by which stabilization could be achieved with plaster. But, as shown by Figure 17, a remarkable increase in strength occurred at 180 days curing time--nearly an 800 per cent

increase in strength between 0 per cent plaster to 50 per cent plaster and a 160 per cent increase above 50 per cent plaster at 28 day curing time.

One explanation for this phenomenon is that the plaster converted to gypsum giving the strength indicated by 1, 7, and 28 day curing times, and the gypsum further increased the strength by a base exchange or a cementing action, as shown by the 180 day curing time.

Plaster of Paris, or gypsum plaster, has a definite potential as a soil stabilizer. It gives a fairly good strength in a short time with the added benefit of increased strength with increased time. This could be an advantage, because close controls of the percentages of plaster added to the soil do not have to be maintained.

Lime-Permian Clay

Lime was chosen as a standard with which to judge the effects of the other admixtures considered in the investigation. Lime has proved to be a very effective stabilizer in the laboratory and in the field. The effects of lime on the strength of Permian clay are illustrated in Figure 18. It is apparent that small percentages of lime will give high strengths. Also, it is clear that there is an optimum lime content of 9 per cent lime for the soil used. This is further demonstrated in Figure 19, which shows the effect of curing time on the strength of Permian clay and lime.

Lime is thought to stabilize soil by the calcium reacting with the available silica and alumina in the soil, forming complicated compounds of non-slaking monocalcium silicates and aluminates. This reaction

is commonly referred to as a pozzolanic reaction. Also, it is believed that carbon dioxide is absorbed from the air and reacts with the calcium hydroxide to form calcium carbonate or limestone.

Figure 20 shows a direct comparison of the results achieved for the different materials used to stabilize Permian clay. The strengths represented are for a 7 day curing time and do not reflect the total strength imparting properties of each stabilizer with increased time of curing. But, as can be readily seen, lime in small percentages is far superior to other stabilizers tested in imparting strength to the clay after a relatively short curing period.

Triaxial Test

Gypsum passing the number 10 sieve and Permian clay were the only combinations tested in triaxial compression. Specimens for the triaxial test were compacted at the same time as the specimens used in the unconfined compression test series. At the time of testing, these specimens had cured for approximately one year.

The type of triaxial test performed was a consolidated-undrained test, which is a test that allows complete consolidation under a certain chamber pressure before any axial load is applied. After consolidation, the specimen is quickly brought to failure by axial loading, without allowing any additional drainage. Data obtained from the tests are plotted, and Mohr's circles of stresses are drawn. An envelope is drawn for the series of circles and this envelope is usually called the strength line. The Y intercept of the line is called the cohesion and denoted as c, and the angle of slope of the line is called the angle of internal

friction and denoted as ϕ. These empirical constants are related to the shear strength of a soil by the equation $s = c + \sigma \tan \phi$, after Coulomb, where σ is the normal stress on the failure plane. In discussing the triaxial tests, reference will be made to c and ϕ only.

Six gypsum contents of 10 through 60 per cent were tested to determine the effect of gypsum on the cohesion and the angle of internal friction of the Permian clay. Chamber pressures of 0.5, 1.0, 2.0 and 4.0 tons/sq.ft. were applied to each gypsum-clay combination for consolidation. The effects of gypsum on the shear strength of Permian clay are depicted in Figures 21 through 26. The changes in the empirical constants are summarized in Table II.

It is evident that with an increase of gypsum there is an increase in the angle of internal friction. Between 10 to 20 per cent gypsum, the increase in ϕ is moderate, but after 20 per cent there is a large increase. No additional effect seems to be obtained for quantities of gypsum in excess of 50 per cent, but a ϕ of 34^{o} for 50 per cent gypsum is about the same as the ϕ of a silty sand in a loose state. The effect of gypsum on the cohesion or c is not so clearly evident. Apparently, gypsum does not have any significant effect upon c of the soil. Care must be exercised in drawing the strength line because slight changes of slope will affect the value of c, and this may be the reason for the variance of the c listed in Table II.

Swell Test

As in the plasticity and triaxial test, only gypsum and Permian clay combinations were investigated. Percentages from 0-30 per cent with

two tests at 50 per cent gypsum were tested using various moisture contents. For each sample, two moisture content determinations, one before and one after testing, were taken to ascertain the amount of water absorbed by the soil. Also the dry unit weight of each specimen was calculated when possible. T. W. Lambe proposed the use of a swelling index, taken as the swelling pressure at the end of 2 hours, for the classification of swelling soils.[16] This was used also for comparative purposes.

Because this is a comparatively new testing device, most of the testing consisted of experimenting with various procedures using the device. The correct moisture content and compaction effort to be used for each gypsum content was not known. Therefore, a set compactive effort of 5 blows per lift, with 3 lifts for each specimen, and various moisture contents were used.

The results of the swelling tests are listed in Table III. Because of the variance of the water content, and probably for various other reasons, no consistent data were obtained. However, it can be concluded that Permian clay, by itself, exhibits considerable swelling pressure, even at high moisture contents. On the other hand, clay and gypsum combinations generally showed significant swelling pressures only at fairly low moisture contents. Also, it seems that there is no added benefit in using percentages of gypsum higher than 10 per cent. Before any conclusive statement can be made on the ability of gypsum to inhibit swelling in Permian clay, a number of additional tests will have to be performed to provide enough data for a statistical study of the results.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

General

This study was concerned with the practicability of using either gypsum, anhydrite or plaster of Paris as a soil stabilizer. The major portion of the investigation was directed toward a study of gypsum. Four basic soil mechanic tests--plasticity, unconfined compression, triaxial and swell tests--were utilized in testing the merits of gypsum as a stabilizer.

Additional studies were made of other calcium sulfate compounds--anhydrite and plaster. Only the unconfined compression test was used in evaluating the effects of anhydrite and plaster as a stabilizer.

The greatest difficulty encountered in the invesigation was controlling the moisture contents. Moisture content variations complicated the interpretation of the data. This difficulty was partially overcome by taking into account, when necessary, the effect which moisture contents, different from the optimum, would have on the strength of the sample. Corresponding corrections were used to adjust the position of the strength curves.

The amount of gypsum passing the number 10 sieve used in this investigation varied from 0-60 per cent for gypsum-Permian clay

combinations and varied from 0-50 per cent for gypsum-bentonite and gypsum-kaolinite combinations. Gypsum passing the 100 sieve was tested with Permian clay in percentages varying from 0-50 per cent. Percentages varying from 0-50 per cent were used in testing anhydrite and plaster of Paris-Permian clay combinations. From the investigation, the following specific conclusions may be drawn:

Gypsum

(1) Gypsum increases the workability of Permain clay by imparting to the soil properties which approach those of cohesionless soil.

(2) Gypsum decreases the optimum moisture content of the soil, but has no apparent effect on the dry density.

(3) Gypsum, passing the number 10 sieve, decreases the unconfined compression strength of the clay for all curing periods up to 180 days.

(4) Gypsum, passing the number 100 sieve, increases the strength of clay, especially after a long curing period.

(5) Gypsum has a minor effect on the strength of bentonite.

(6) Gypsum increases the strength of kaolinite

(7) Gypsum increases the angle of internal friction, while it has a minor effect on the cohesion of Permian red clay.

(8) Gypsum has the ability to reduce the intensity of swell pressure exhibited by Permian clay.

With the addition of gypsum passing the number 10 sieve there is no apparent increase in strength at the curing periods tested. However,

gypsum does impart workability, friability and reduced swelling. This type of stabilization might be considered a physical stabilization because there were no indications of a chemical reaction.

Reducing the particle size of gypsum increases the strength of the clay after 180 days curing time. The samples tested were drier than at compaction, but this would not entirely explain the large increase in strength. Evidently, the finer gypsum takes part in a cationic exchange and increases the strength of the Permian clay.

Anhydrite

(1) For a long curing period, anhydrite will impart substantial strength to Permian clay.

(2) Anhydrite increases workability and gives the soil a loose friable appearance.

(3) Anhydrite does not change the optimum moisture content or the dry density of Permian red clay.

Anhydrite has the ability to give added strength to Permian clay, but only after a considerable curing period. This would place definite limitations on the use of anhydrite as a stabilizer. Further testing would have to be accomplished to determine the effect of anhydrite on the other soil properties important in stabilization before a complete evaluation of anhydrite as a soil stabilizer could be made.

Plaster of Paris

(1) Plaster increases the workability of Permian clay before the plaster sets up.

(2) Plaster increases the optimum moisture content of Permian clay and has no apparent effect on the dry density.

(3) Plaster greatly increases the strength after a short period of curing.

(4) Further increases of strength occur after a curing period of 180 days.

Of the three admixtures investigated, plaster shows the most promise as a soil stabilizer. In approximately 8 hours an increase of strength is given to the clay; as an example, for a plaster content of 20 per cent, there is a 300 per cent increase in strength for 8 hours curing time. After the initial increase in strength, an added increase in strength is shown with increasing time of curing.

Only the unconfined compression test was used in testing the effect of plaster on Permian clay. Therefore, additional investigations should be made to permit a complete evaluation of the suitability of plaster for use in soil stabilization.

Recommendations for Future Research

The following recommendations are suggested for future research to investigate the effectiveness of gypsum, anhydrite or plaster of Paris as soil stabilizers:

(1) Further investigations into the effect of anhydrite and plaster of Paris on the plasticity, swelling ability and shearing strength parameters of Permian red clay.

(2) Investigation to discover whether calcium sulfate compounds deteriorate concrete or bituminous pavements.

(3) Determination of the effectiveness of gypsum, anhydrite or plaster of Paris stabilization when specimens containing these admixtures are subjected to weathering.

(4) Investigation into the effect of reducing the particle size of gypsum, anhydrite or plaster of Paris to hasten the increase in strength and to increase the magnitude of strength in Permian red clay.

(5) Economic studies of the feasibility of gypsum, anhydrite, or plaster of Paris stabilization.

(6) Investigation into the effect of trace chemicals on the stabilizing effect of gypsum, anhydrite or plaster of Paris.

(7) Actual field testing of roadways stabilized with either gypsum, anhydrite or plaster of Paris.

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TABLE I

PROPERTIES OF THE CLAY MATERIALS

Clay	LL	PL	PI	Base Exchange m.e./100 gms.
Permian Red	41	15	26	13.0
Bentonite	603	42	561	66.2
Kaolinite	61	32	29	3.2

TABLE II

EFFECT OF GYPSUM ON c AND ϕ OF PERMIAN CLAY

% Gypsum	ϕ	c(tons/sq.ft.)
10	12°	0.6
20	14°	0.4
30	24°	0.3
40	31°	0.1
50	34°	0.4
60	35°	0.4

TABLE III

RESULTS OF THE SWELL TEST

Moisture Content				
At Compaction Per Cent	At Testing Per Cent	After Testing Per Cent	Dry Unit Weight lb./cu.ft.	Swell Pressure at 2 Hours lb./sq.in.
		0% Gypsum		
17.0	17.7	19.4	107.2	6.1
17.0	--	--	--	12.3
17.0	15.1	--	--	6.9
16.0	15.4	16.4	111.9	6.6
15.0	15.1	17.0	--	10.9
15.0	15.6	18.0	121.1	7.5
14.0	15.4	15.3	118.1	8.2
11.0	--	--	110.0	31.4
9.0	6.0	14.8	117.0	18.5
		10% Gypsum		
16.0	14.5	15.1	110.0	5.6
12.0	--	11.5	120.0	12.5
11.0	14.0	12.0	118.9	11.3
10.0	12.5	10.9	123.0	17.7
		20% Gypsum		
--	12.4	--	115.8	11.0
--	17.5	--	103.2	4.3
11.0	13.1	10.8	122.2	11.1
10.0	14.0	12.5	126.6	8.9
9.0	10.1	11.7	136.0	15.3

TABLE III (Continued)

Moisture Content				
At Compaction	At Testing	After Testing	Dry Unit Weight	Swell Pressure at 2 Hours
Per Cent	Per Cent	Per Cent	lb./cu.ft.	lb./sq.in.
		30% Gypsum		
--	11.8	14.7	113.8	3.6
10.0	13.1	4.9	116.2	10.6
9.0	10.2	15.4	124.0	10.3
8.0	10.6	12.1	123.0	7.9
		50% Gypsum		
13.0	9.6	11.4	121.4	3.5
8.0	10.8	15.7	119.3	7.2

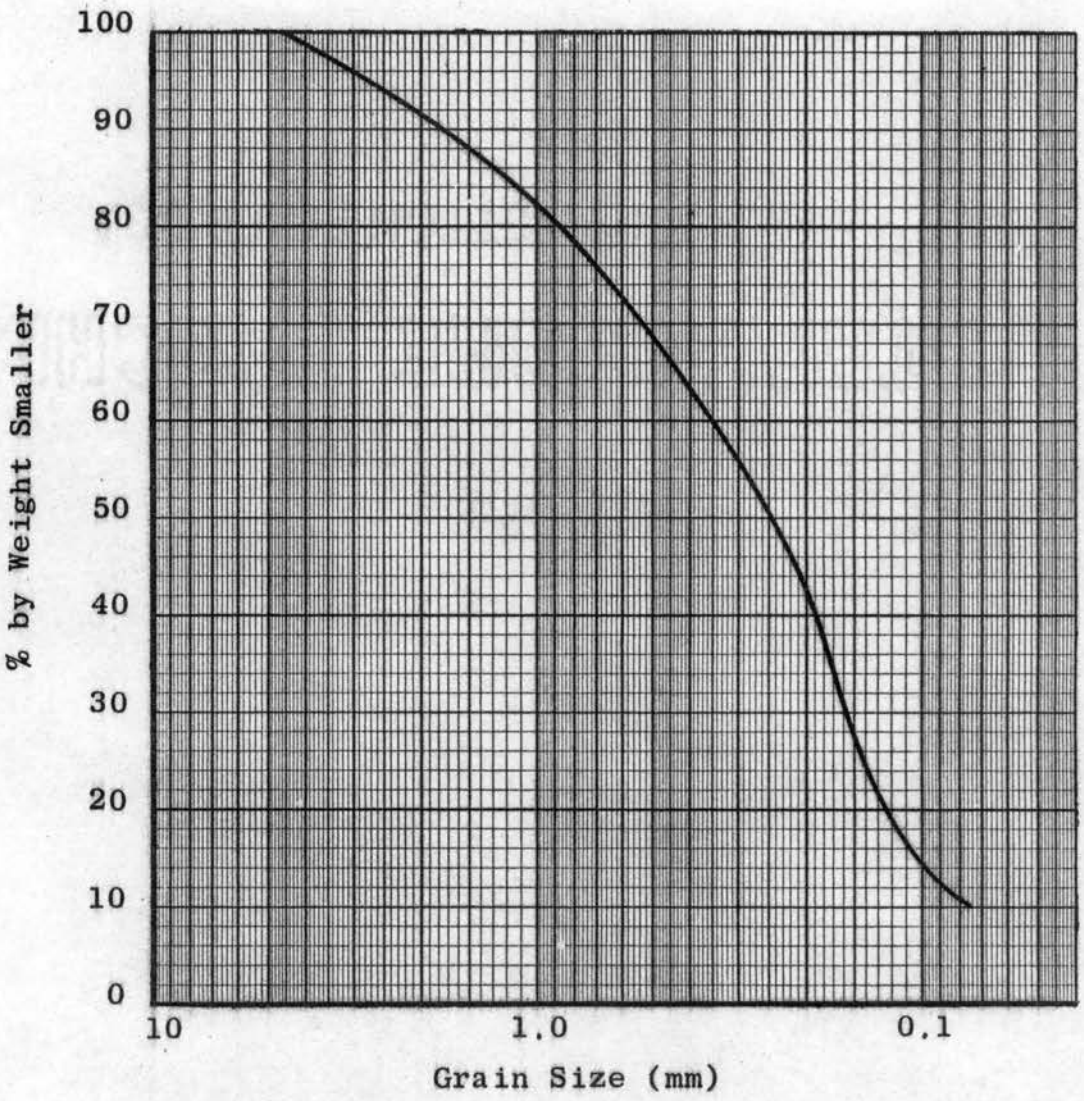

FIGURE 1

GRAIN SIZE DISTRIBUTION CURVE FOR GYPSUM

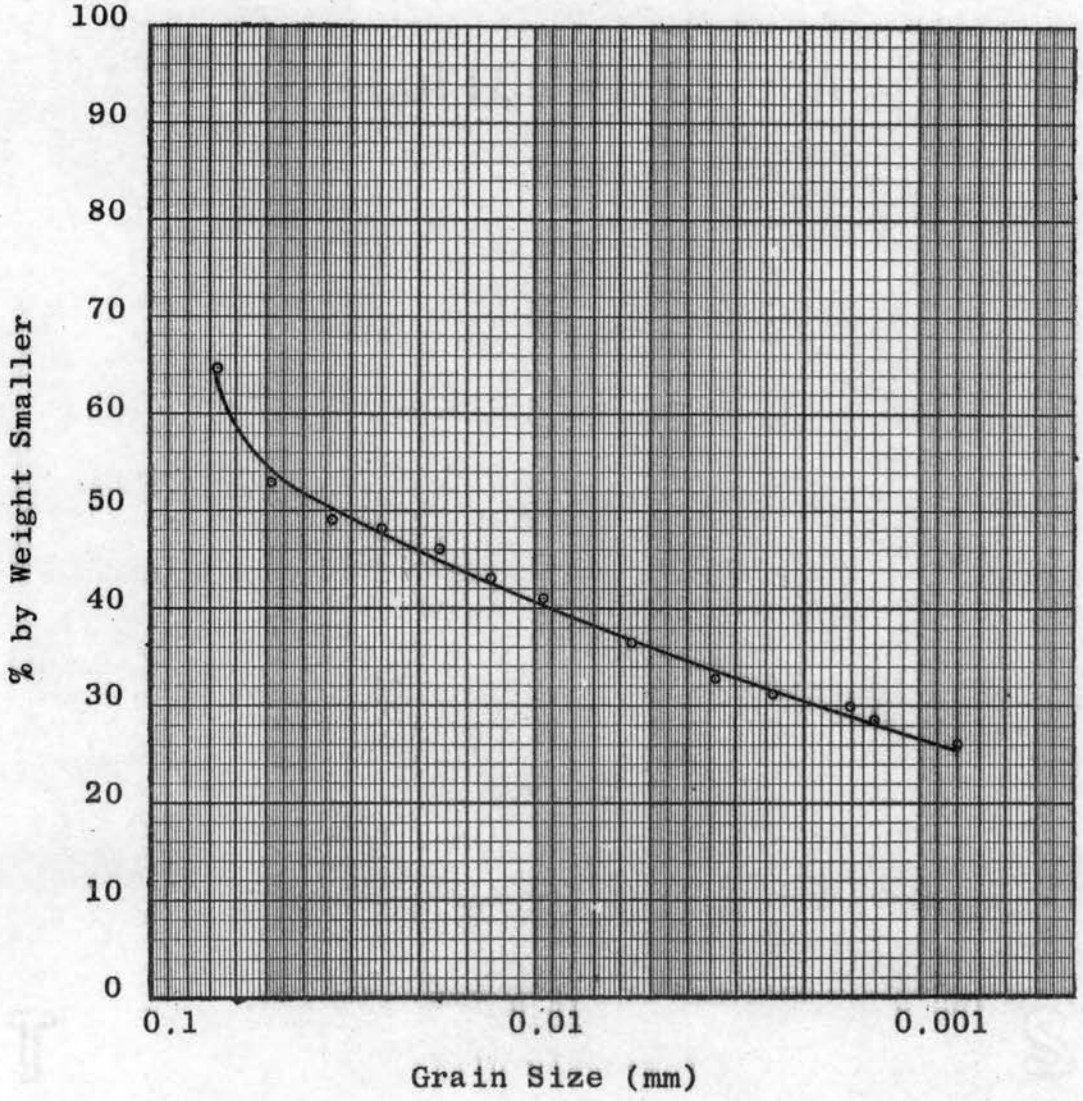

FIGURE 2

GRAIN SIZE DISTRIBUTION CURVE FOR
PERMIAN RED CLAY

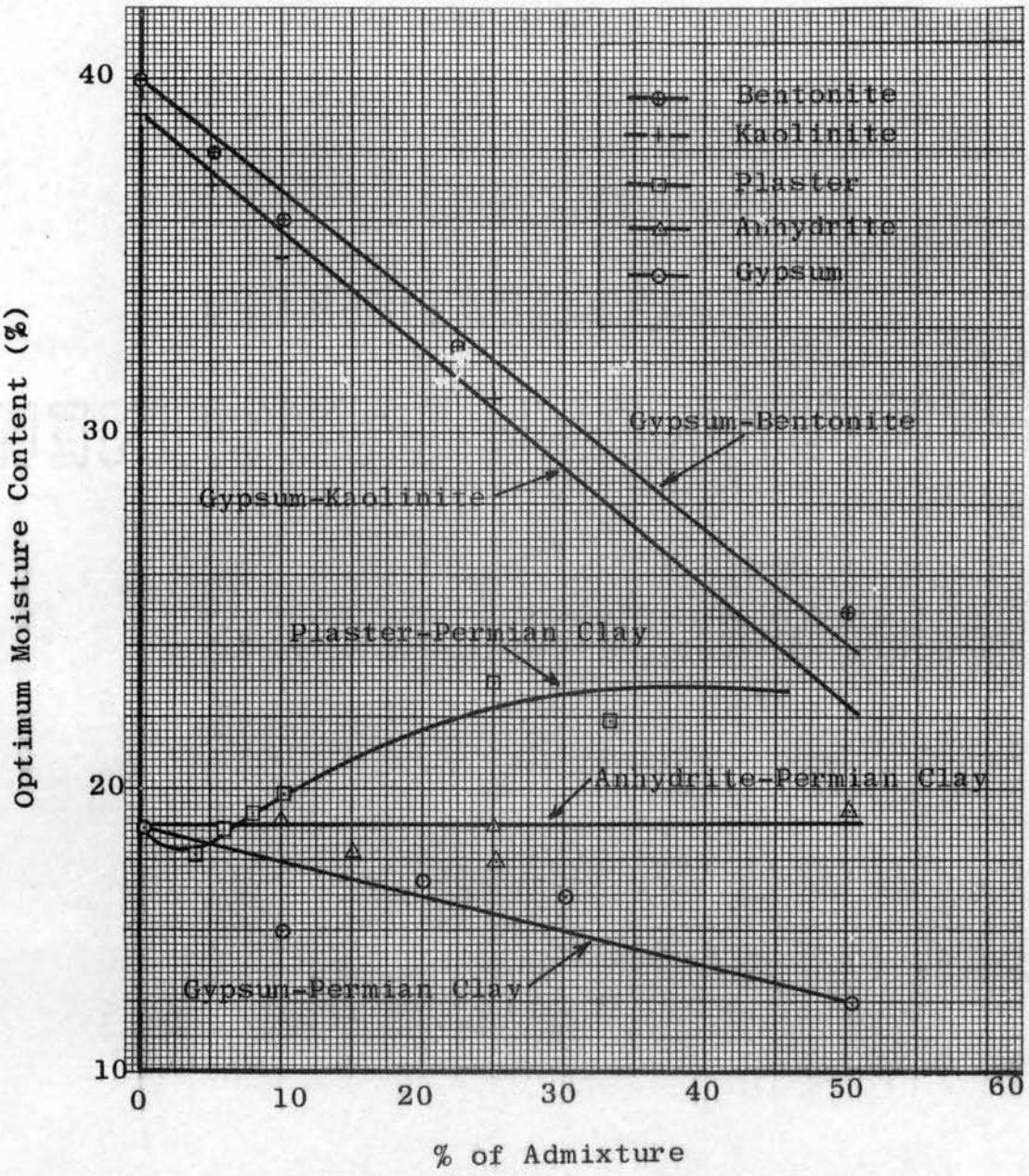

FIGURE 3

RELATIONSHIP BETWEEN OPTIMUM MOISTURE CONTENT AND PERCENT ADMIXTURE FOR VARIOUS COMBINATIONS OF MATERIALS

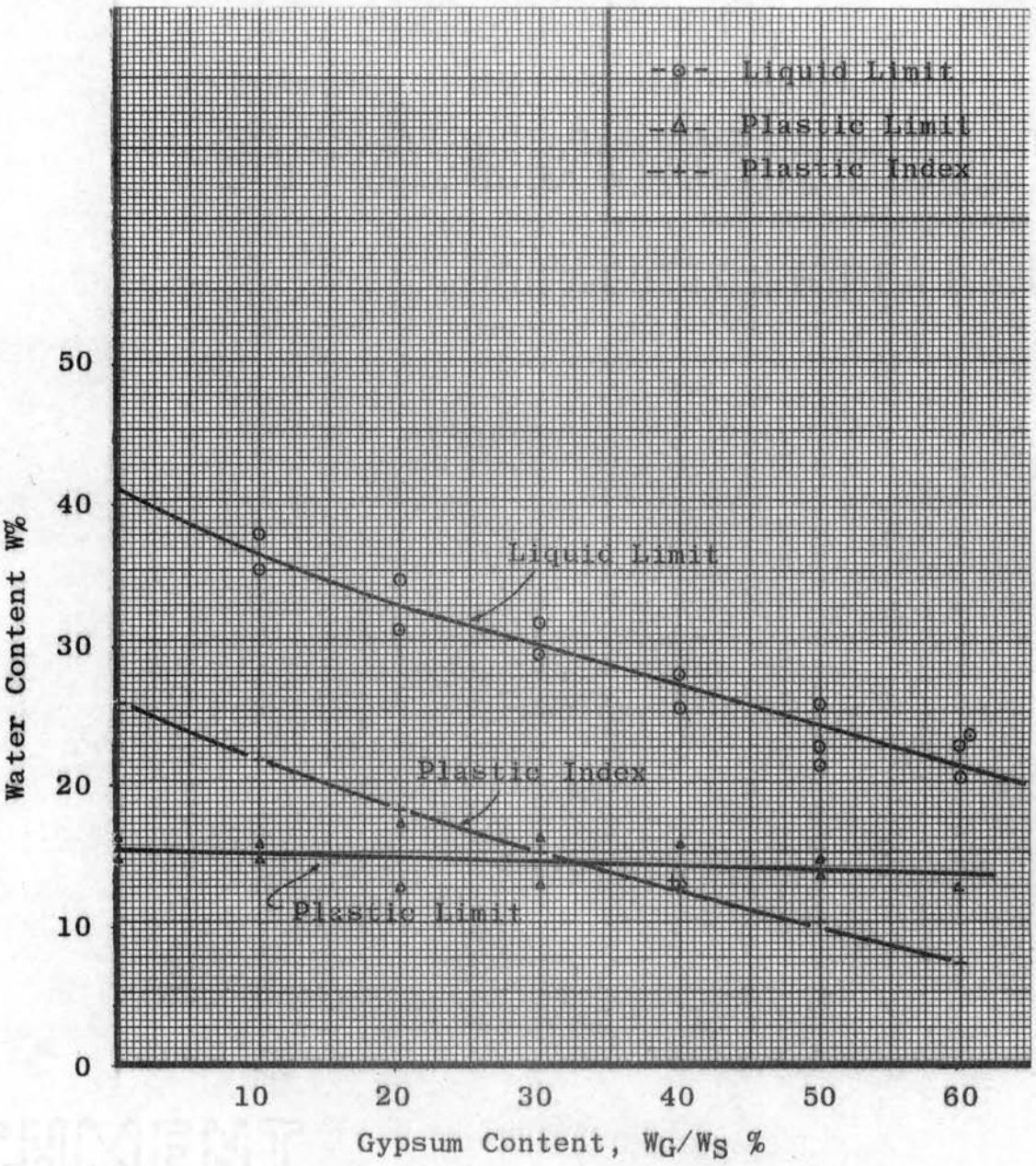

FIGURE 4

EFFECT OF GYPSUM
ON
PLASTICITY OF PERMIAN CLAY

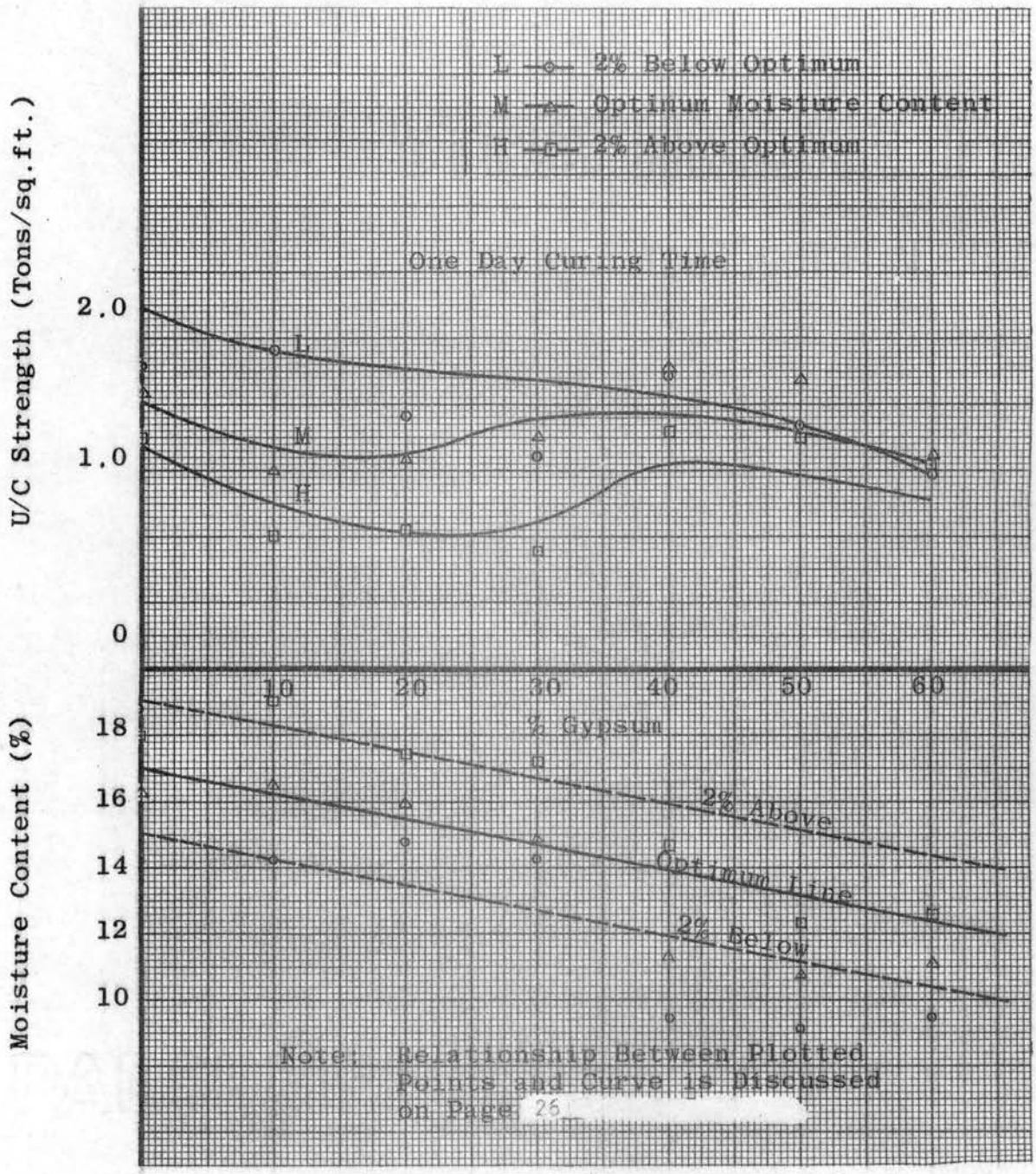

FIGURE 5

EFFECT OF GYPSUM CONTENT
ON THE
STRENGTH OF PERMIAN CLAY

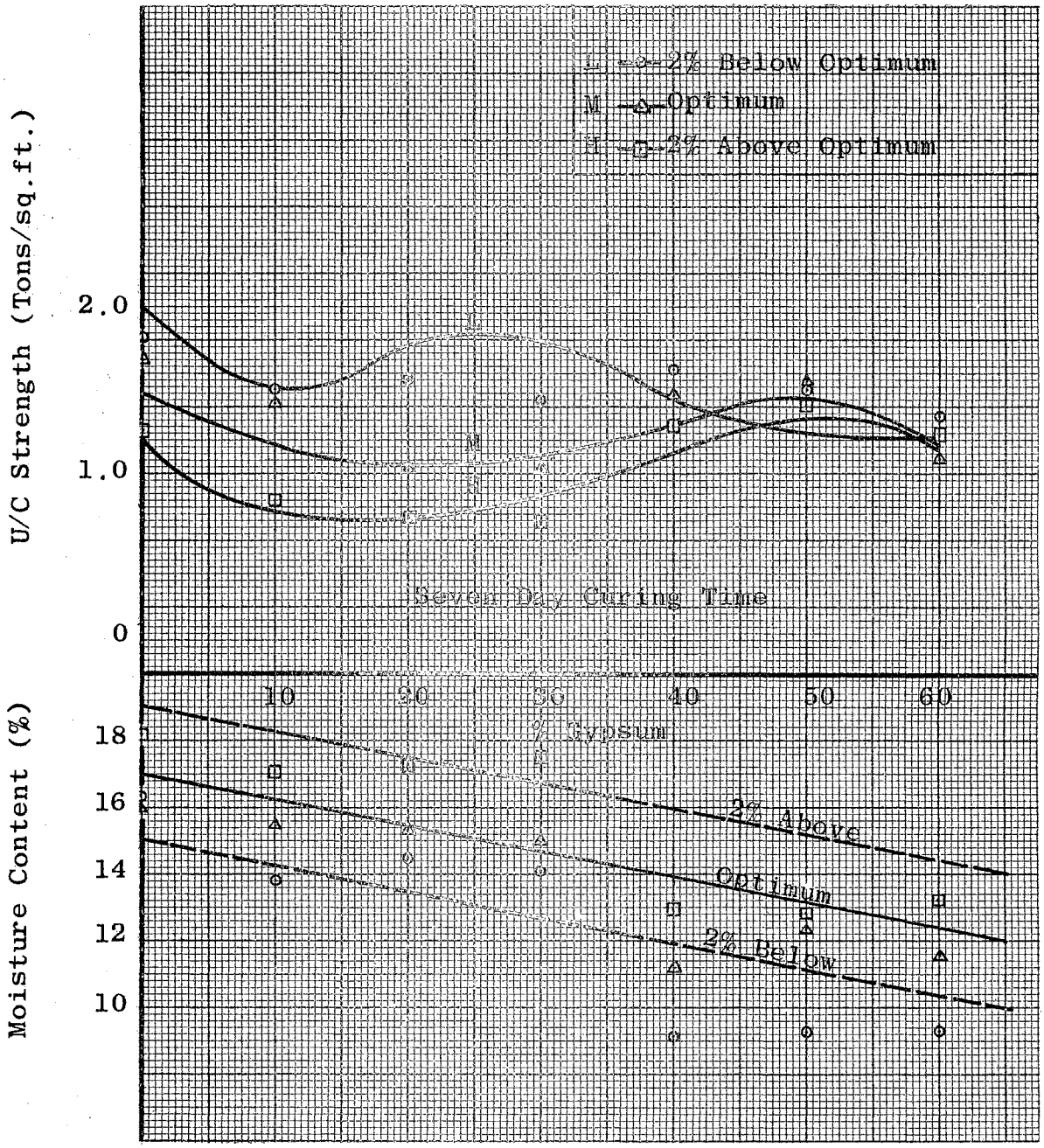

FIGURE 6

EFFECT OF GYPSUM CONTENT
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STRENGTH OF PERMIAN CLAY

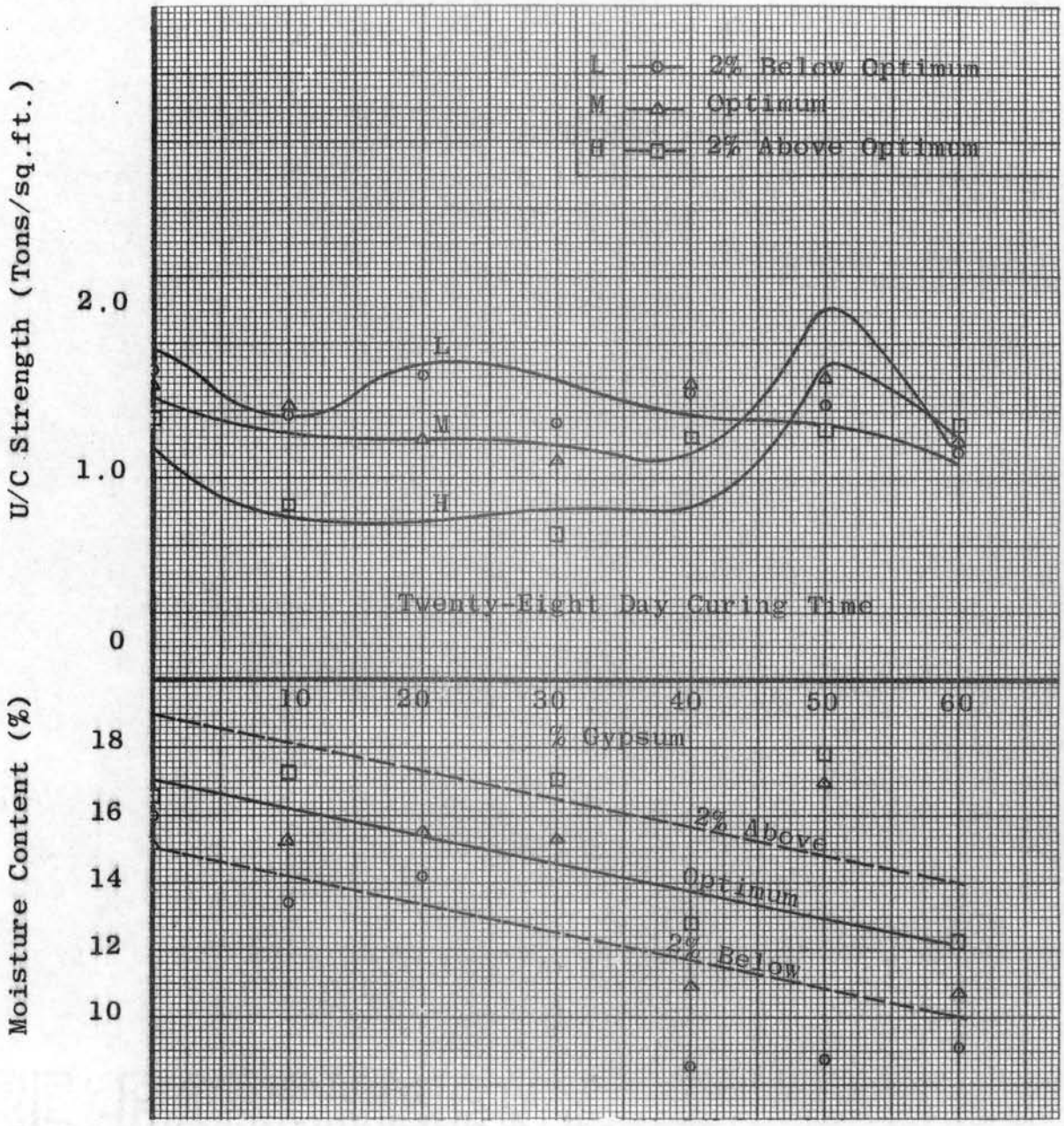

FIGURE 7

EFFECT OF GYPSUM CONTENT
ON THE
STRENGTH OF PERMIAN CLAY

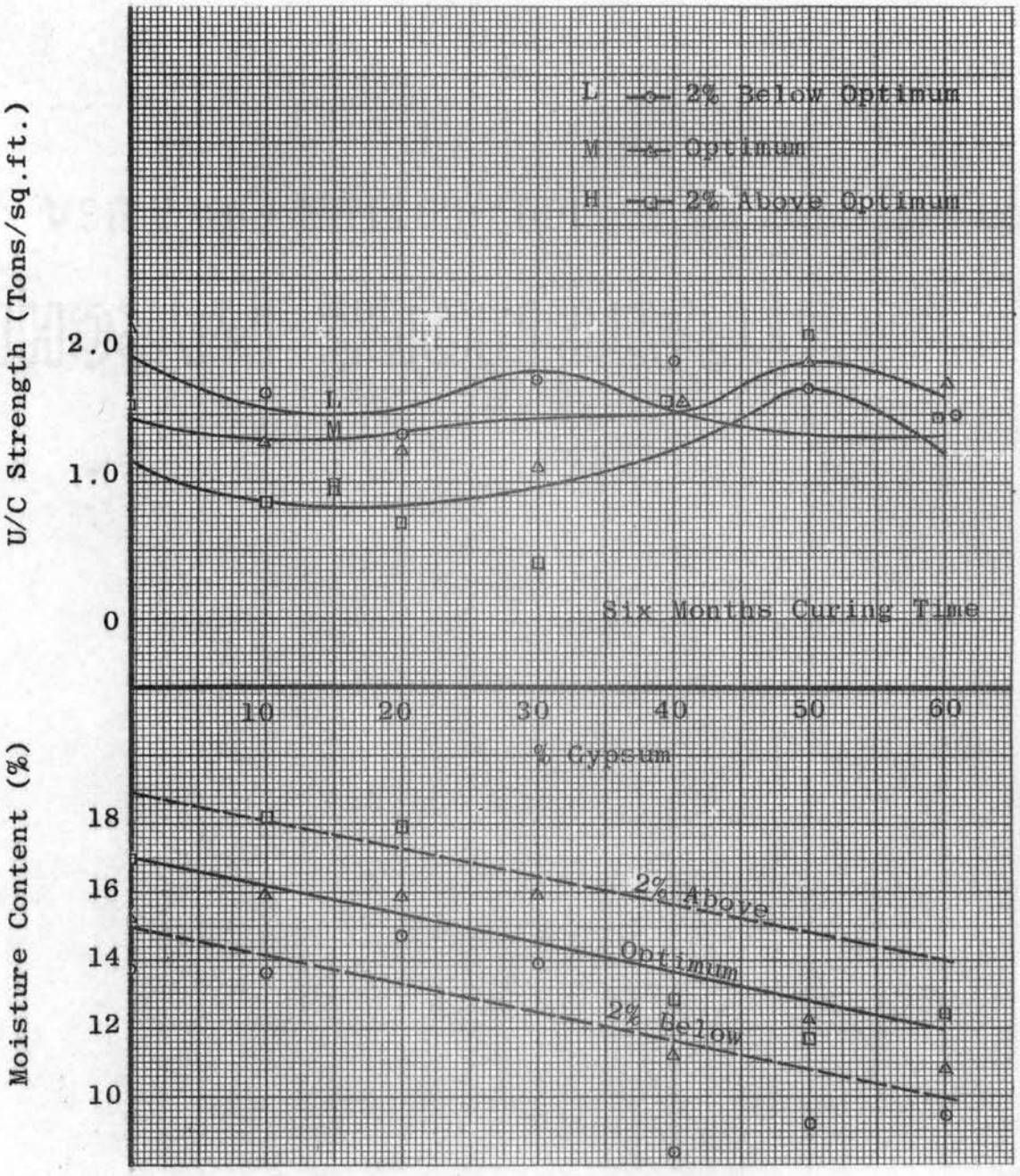

FIGURE 8

EFFECT OF GYPSUM CONTENT
ON THE
STRENGTH OF PERMIAN CLAY

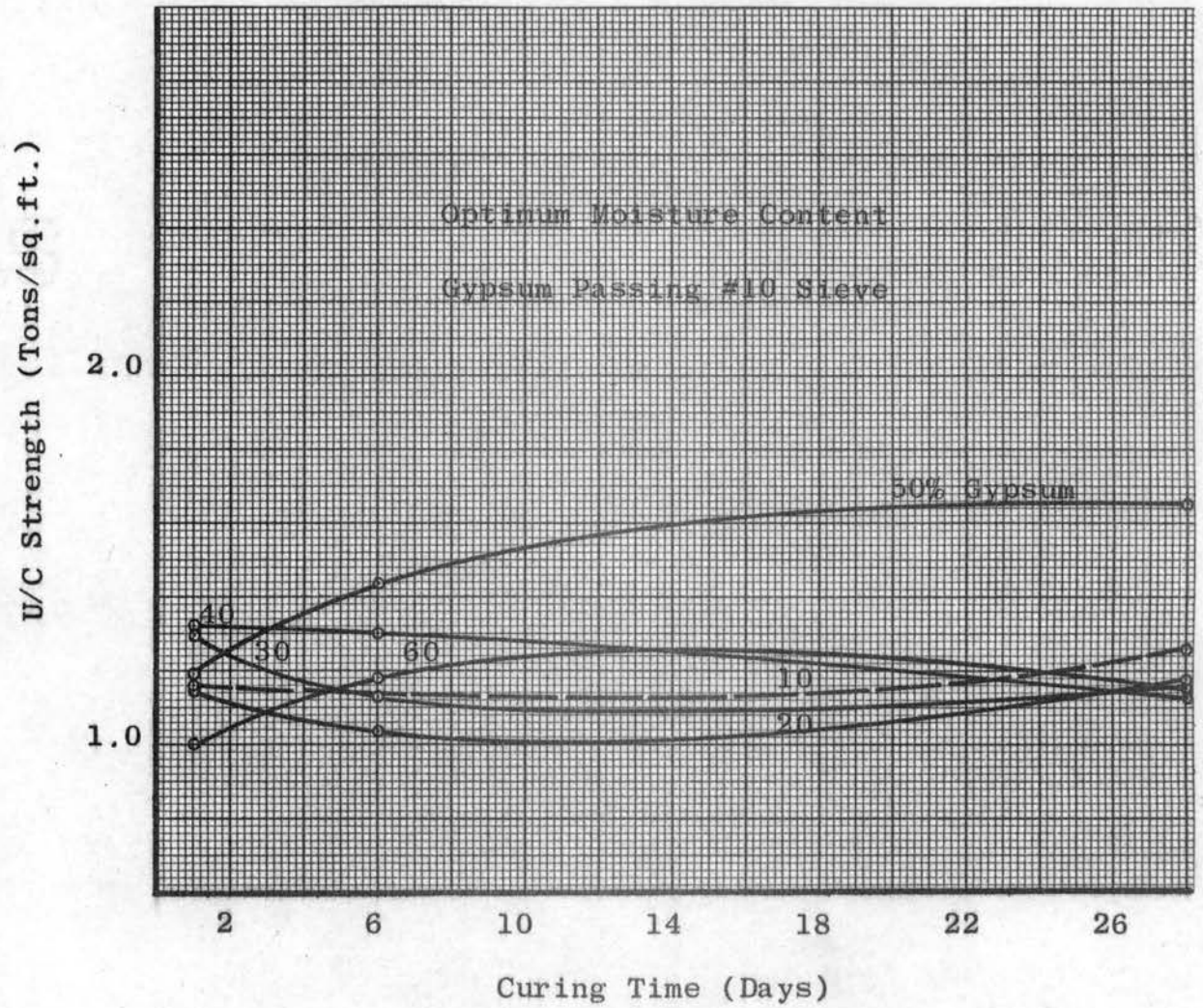

FIGURE 9

EFFECT OF CURING TIME
ON THE
STRENGTH OF PERMIAN CLAY AND GYPSUM

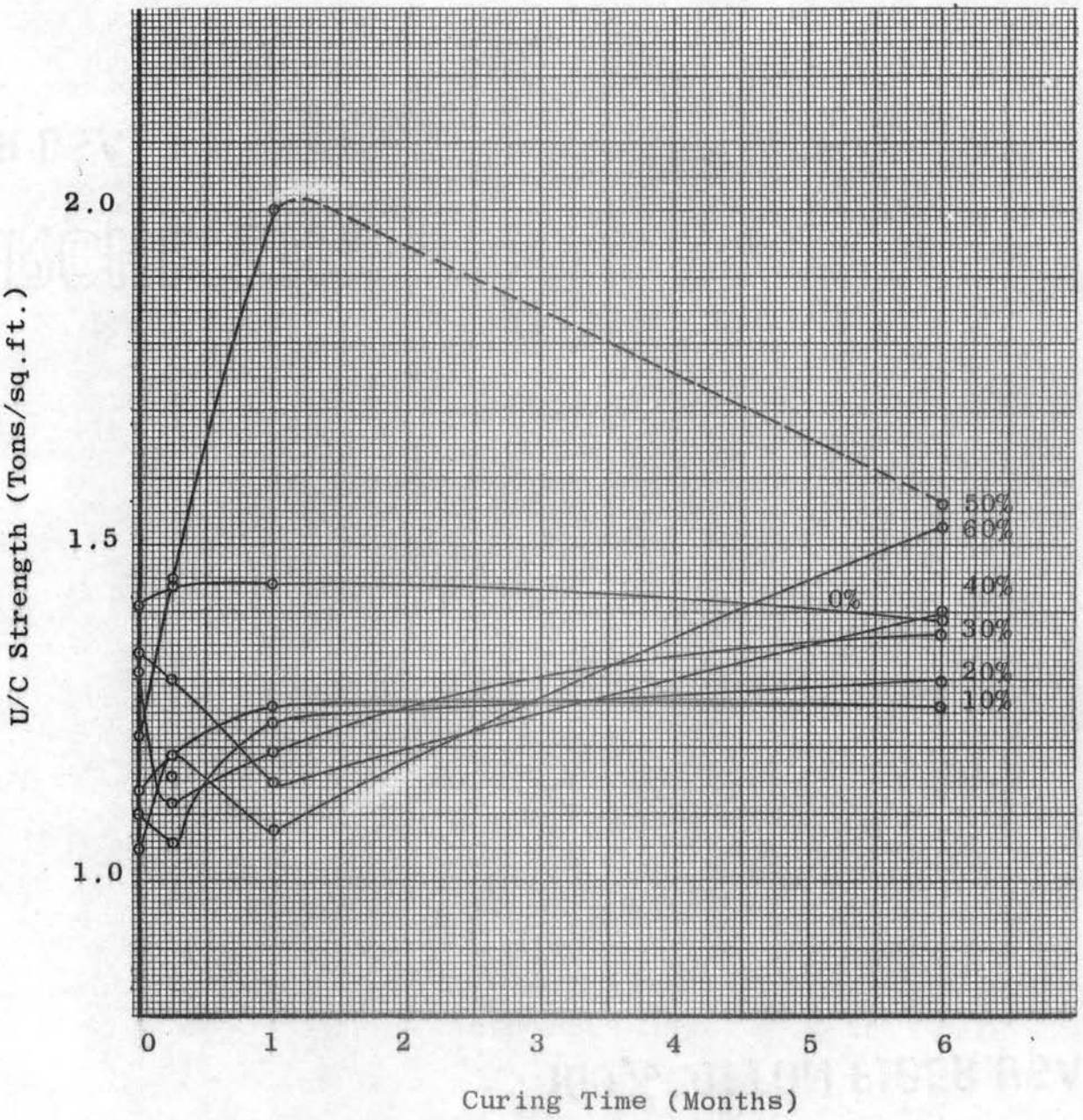

FIGURE 10

EFFECT OF CURING TIME
ON THE
STRENGTH OF PERMIAN CLAY AND GYPSUM

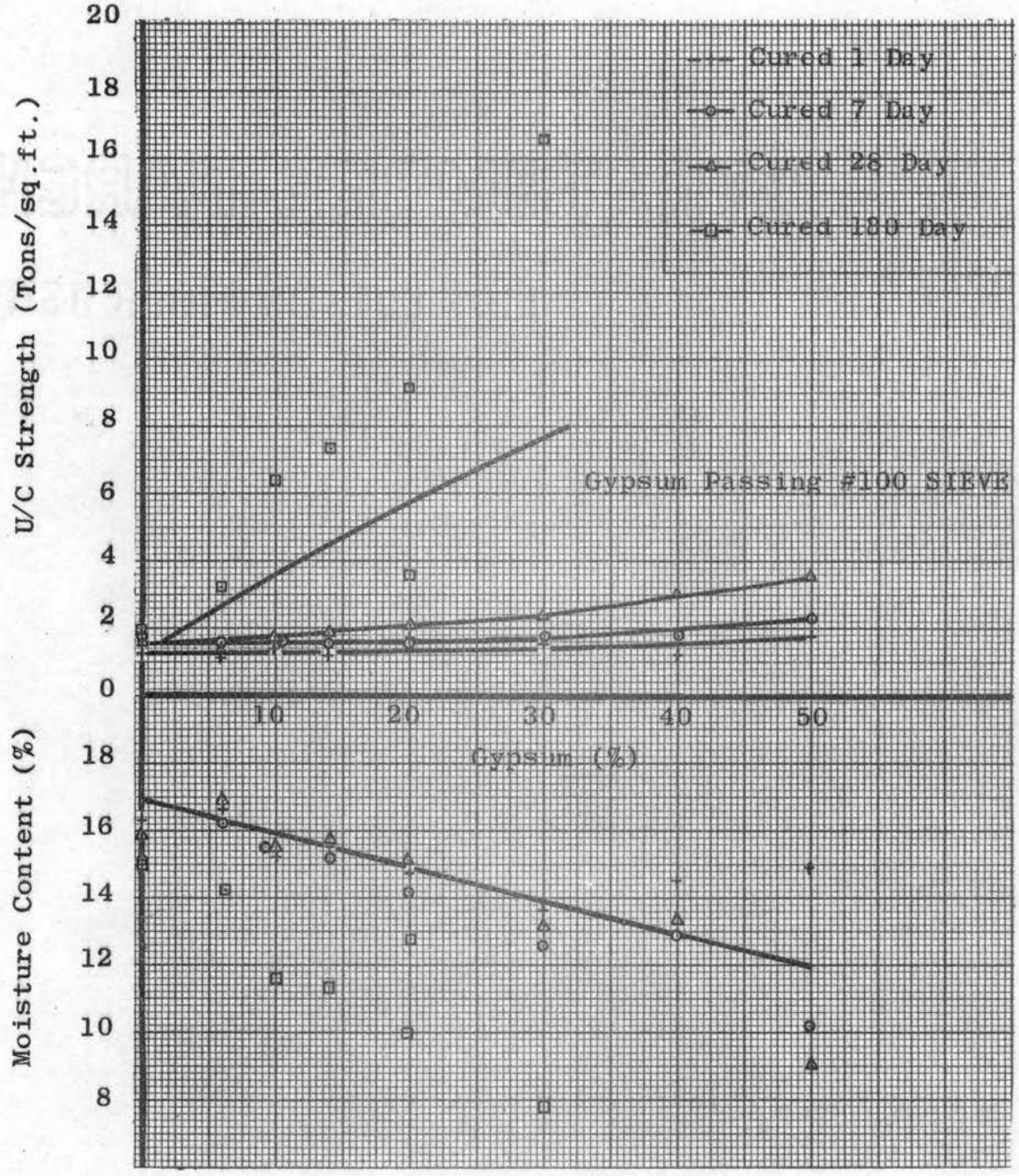

FIGURE 11

EFFECT OF GYPSUM CONTENT ON THE
UNCONFINED COMPRESSIVE
STRENGTH OF PERMIAN CLAY

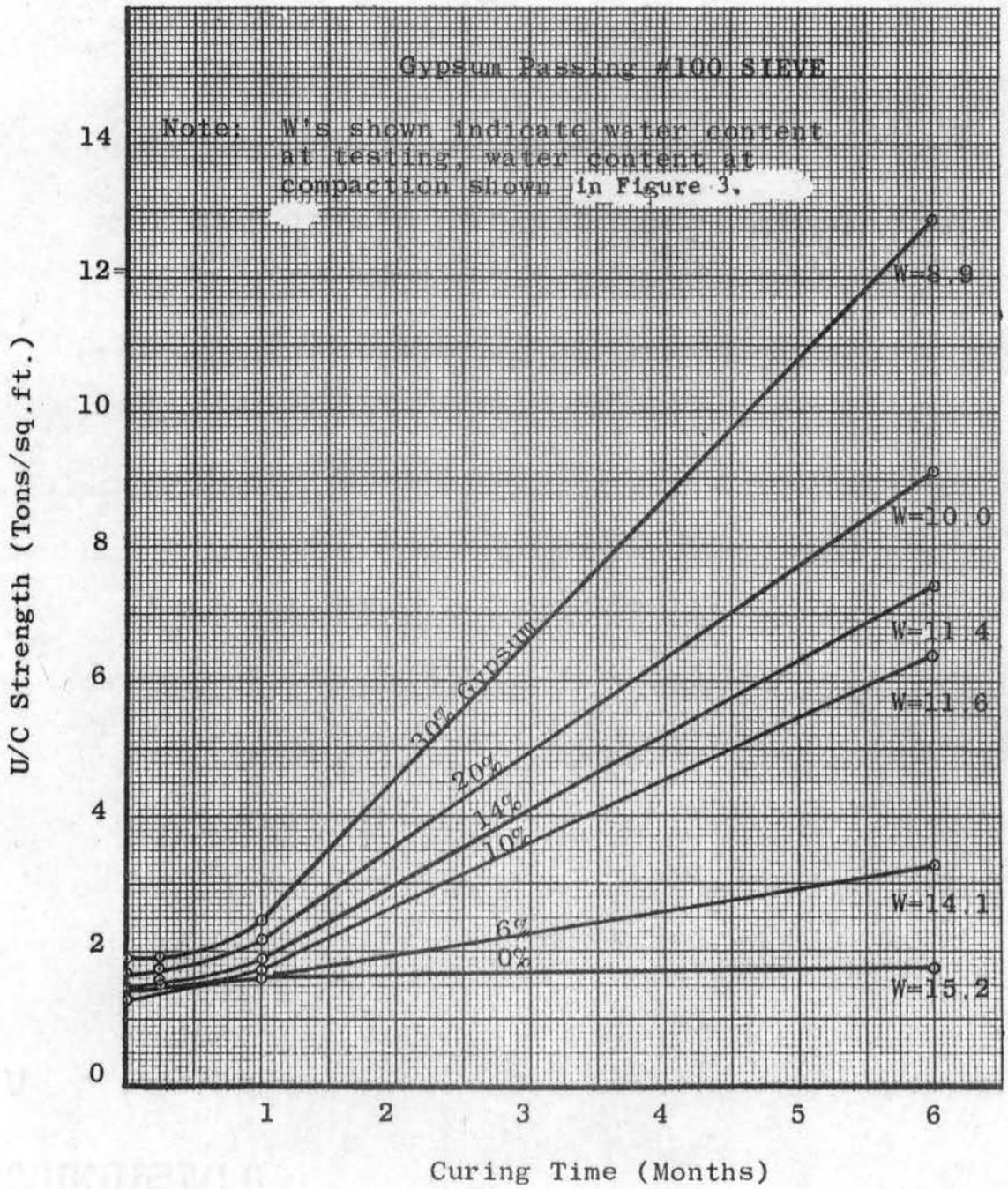

FIGURE 12

EFFECT OF CURING TIME
ON THE
STRENGTH OF PERMIAN CLAY AND GYPSUM

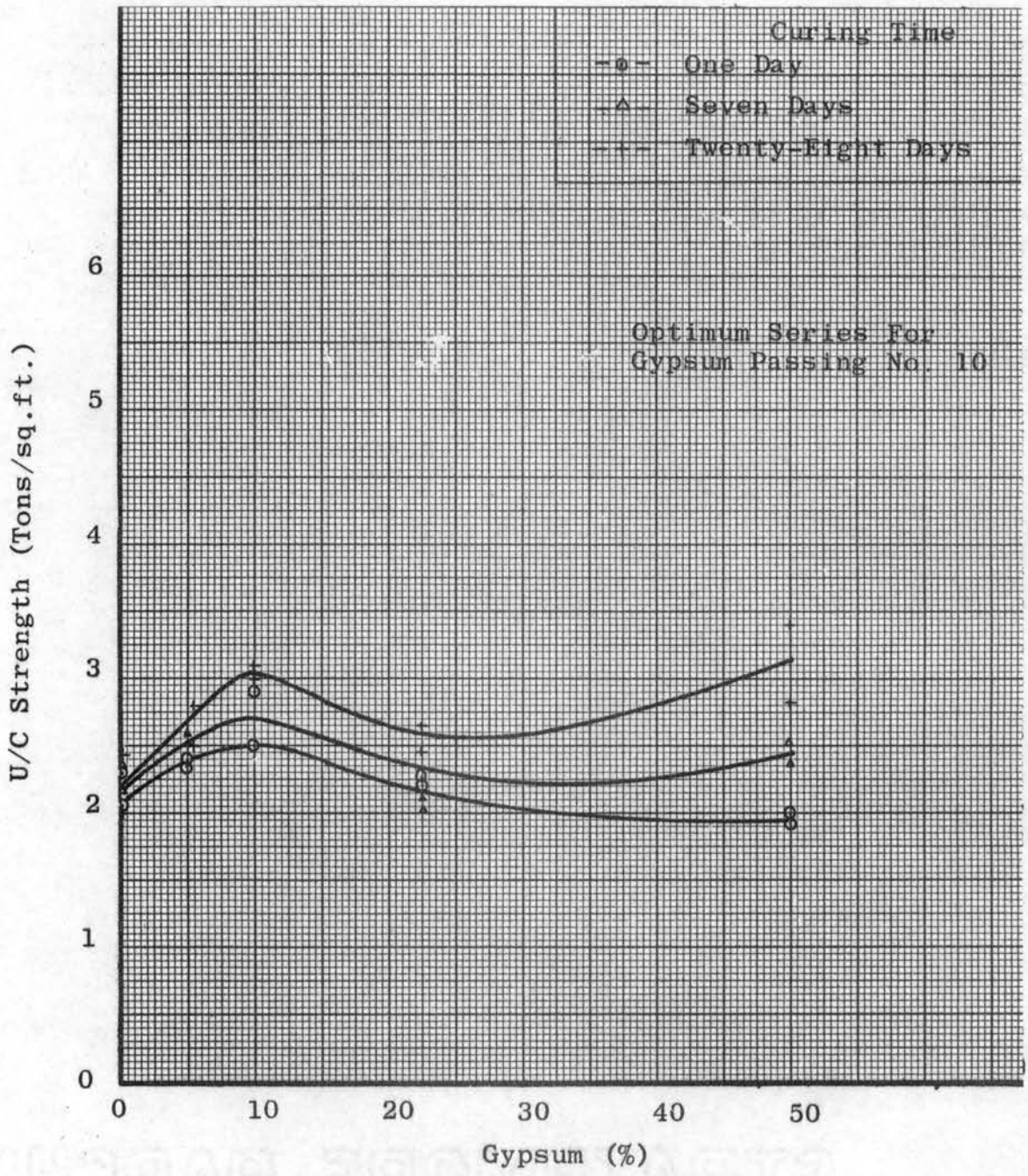

FIGURE 13

EFFECT OF GYPSUM
ON THE UNCONFINED COMPRESSIVE
STRENGTH OF BENTONITE

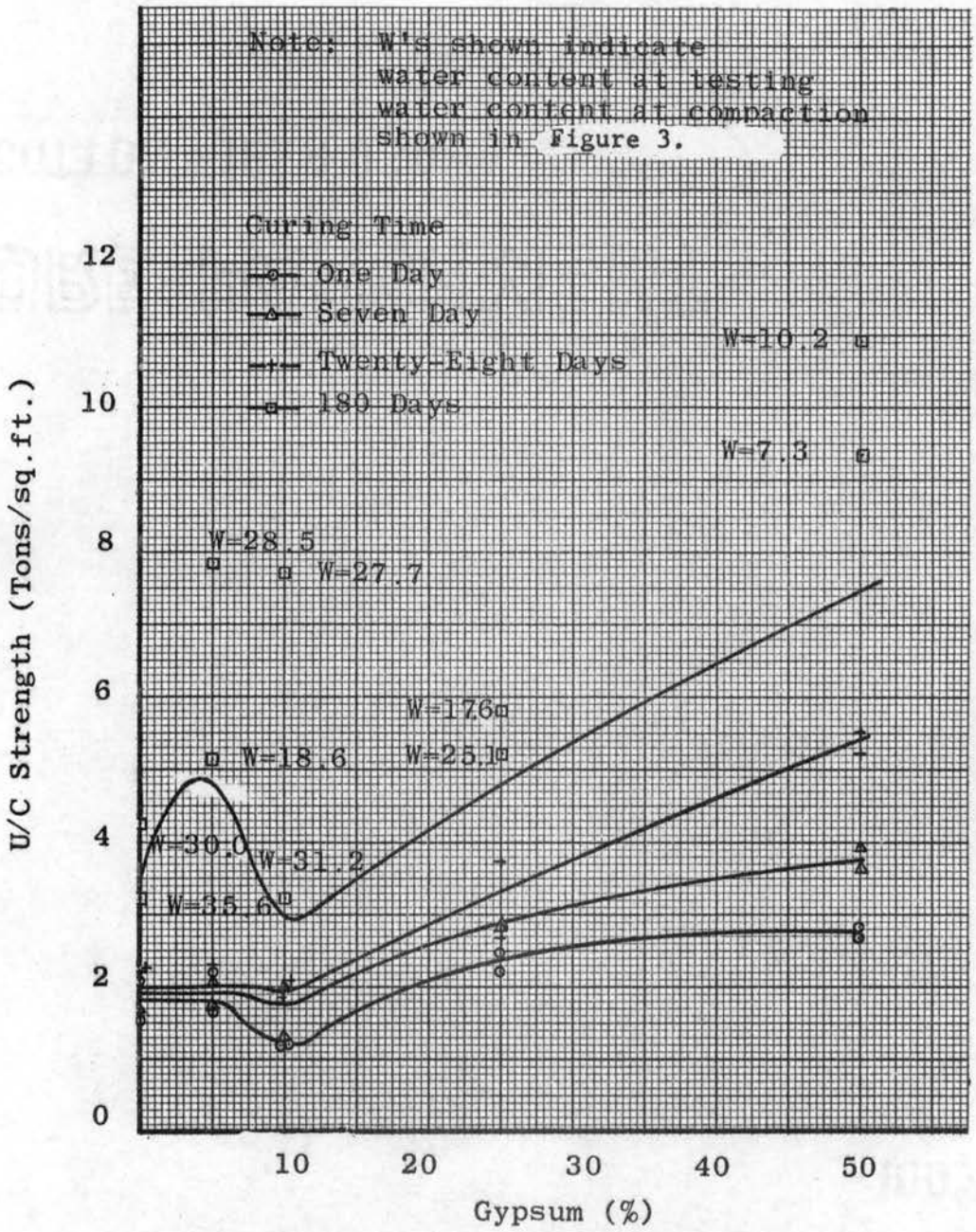

FIGURE 14

EFFECT OF GYPSUM ON THE UNCONFINED COMPRESSIVE STRENGTH OF KAOLINITE

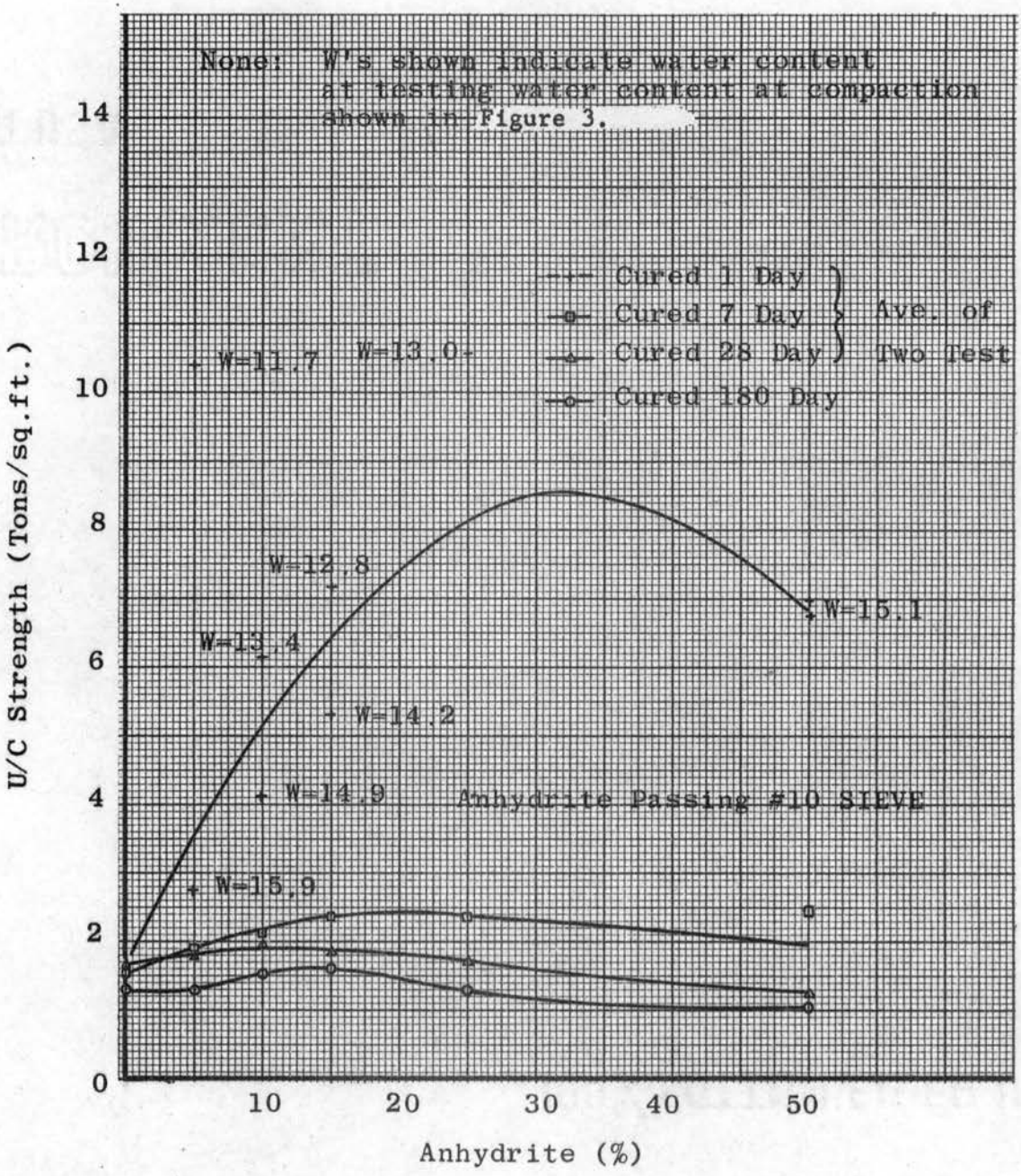

FIGURE 15

EFFECT OF ANHYDRITE CONTENT
ON THE UNCONFINED COMPRESSIVE
STRENGTH OF PERMIAN CLAY

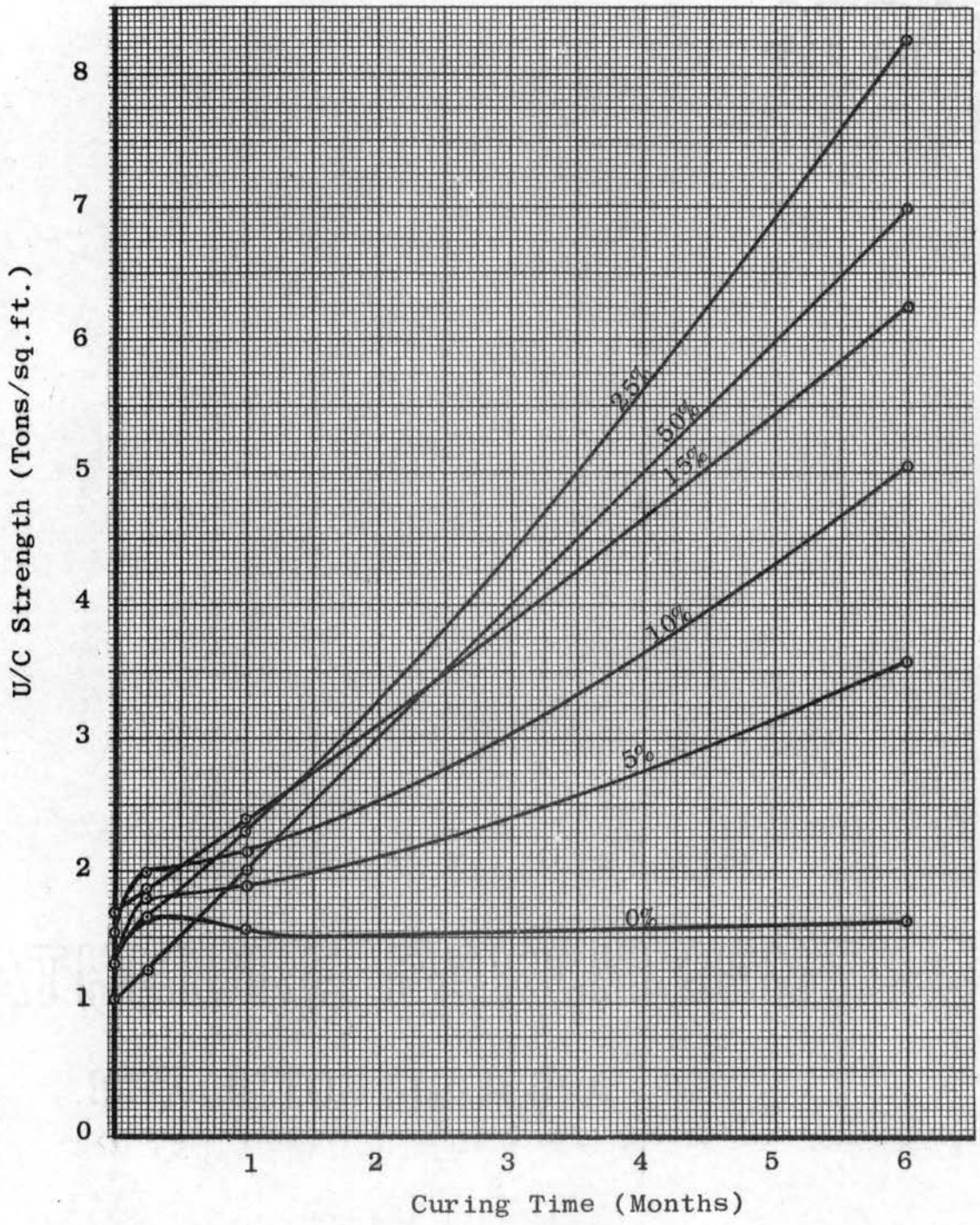

FIGURE 16

EFFECT OF CURING TIME
ON THE
STRENGTH OF ANHYDRITE AND PERMIAN CLAY

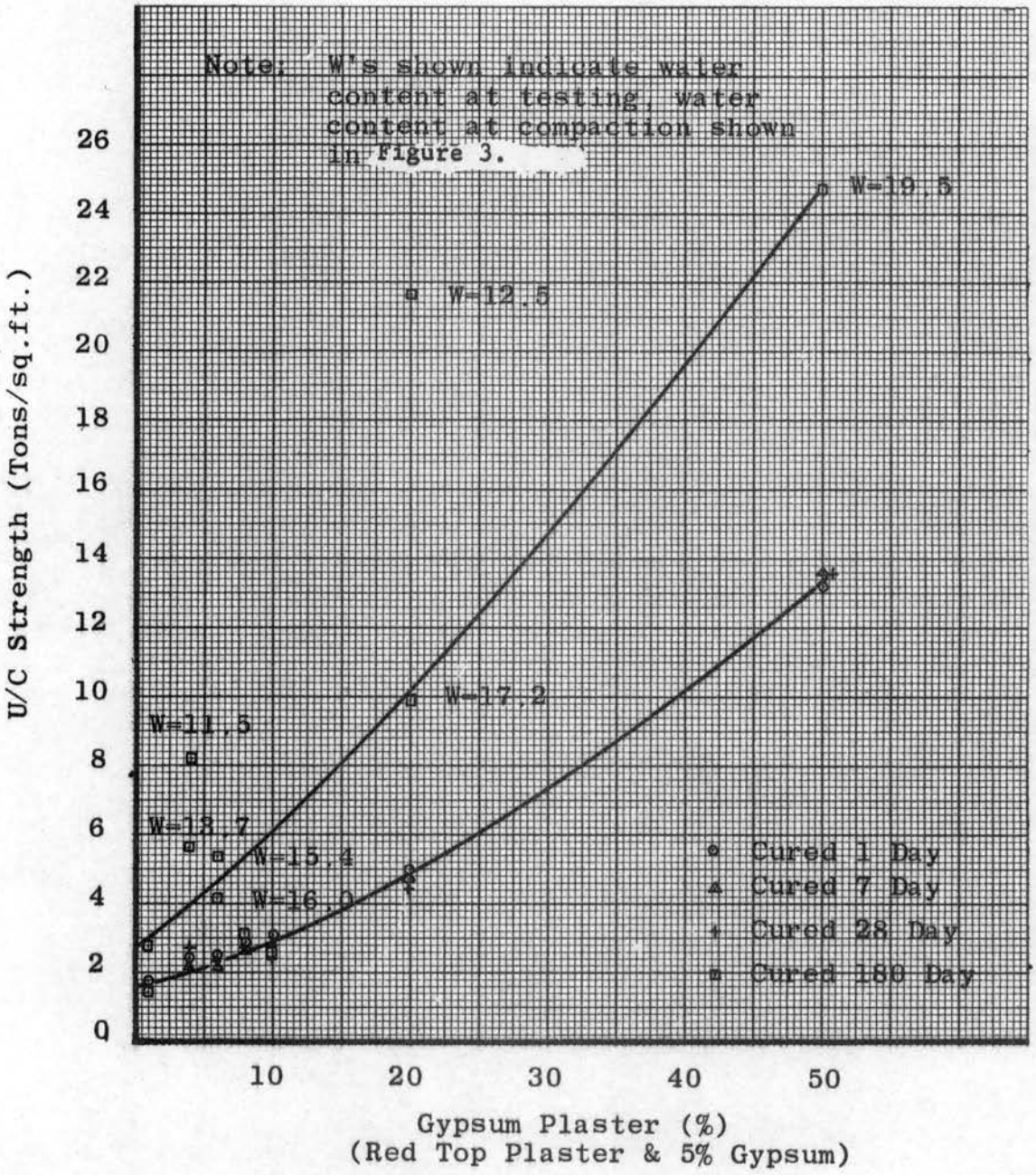

FIGURE 17

EFFECT OF GYPSUM PLASTER
ON THE UNCONFINED COMPRESSIVE
STRENGTH OF PERMIAN CLAY

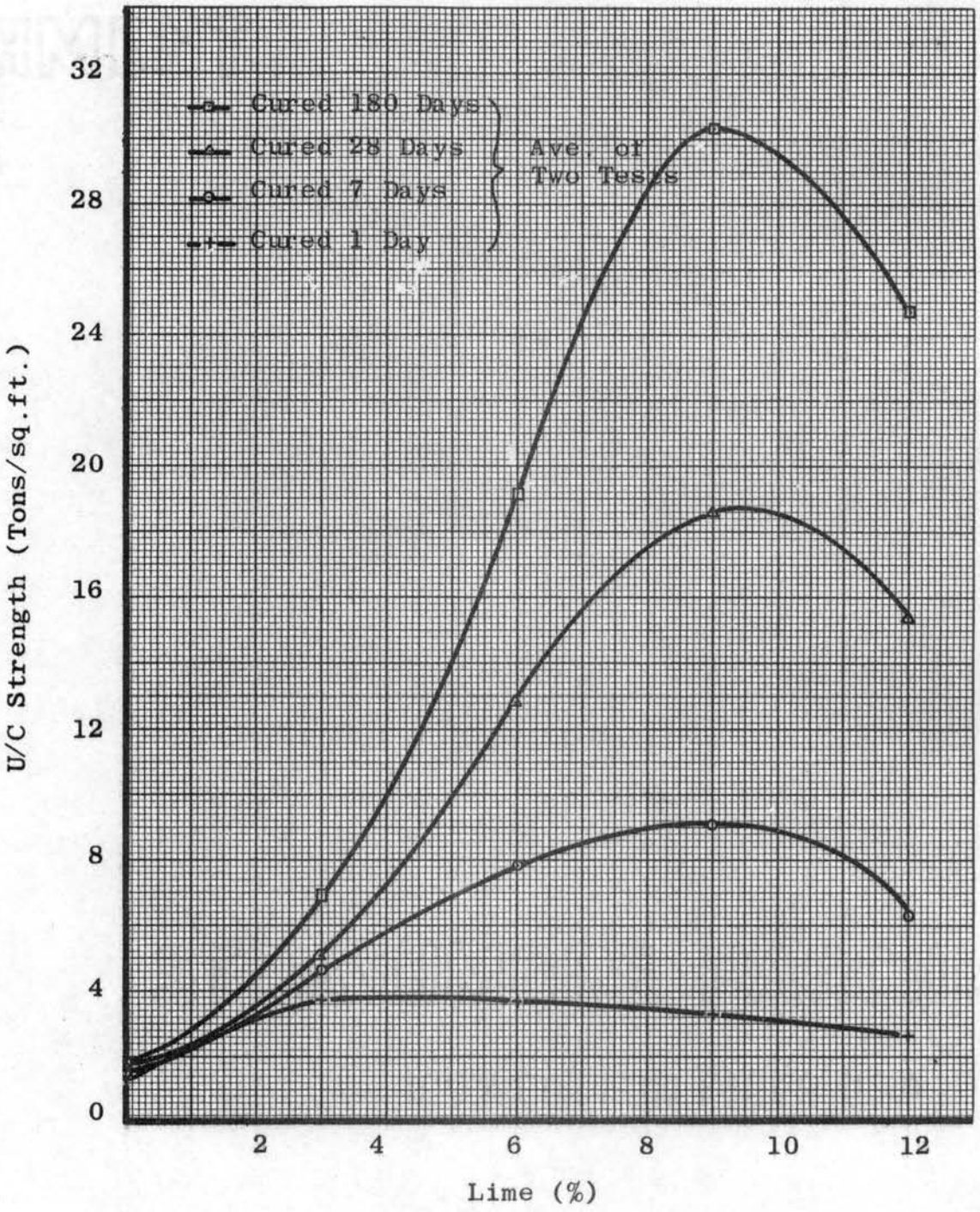

FIGURE 18

EFFECT OF LIME ON THE UNCONFINED COMPRESSIVE STRENGTH OF PERMIAN CLAYS

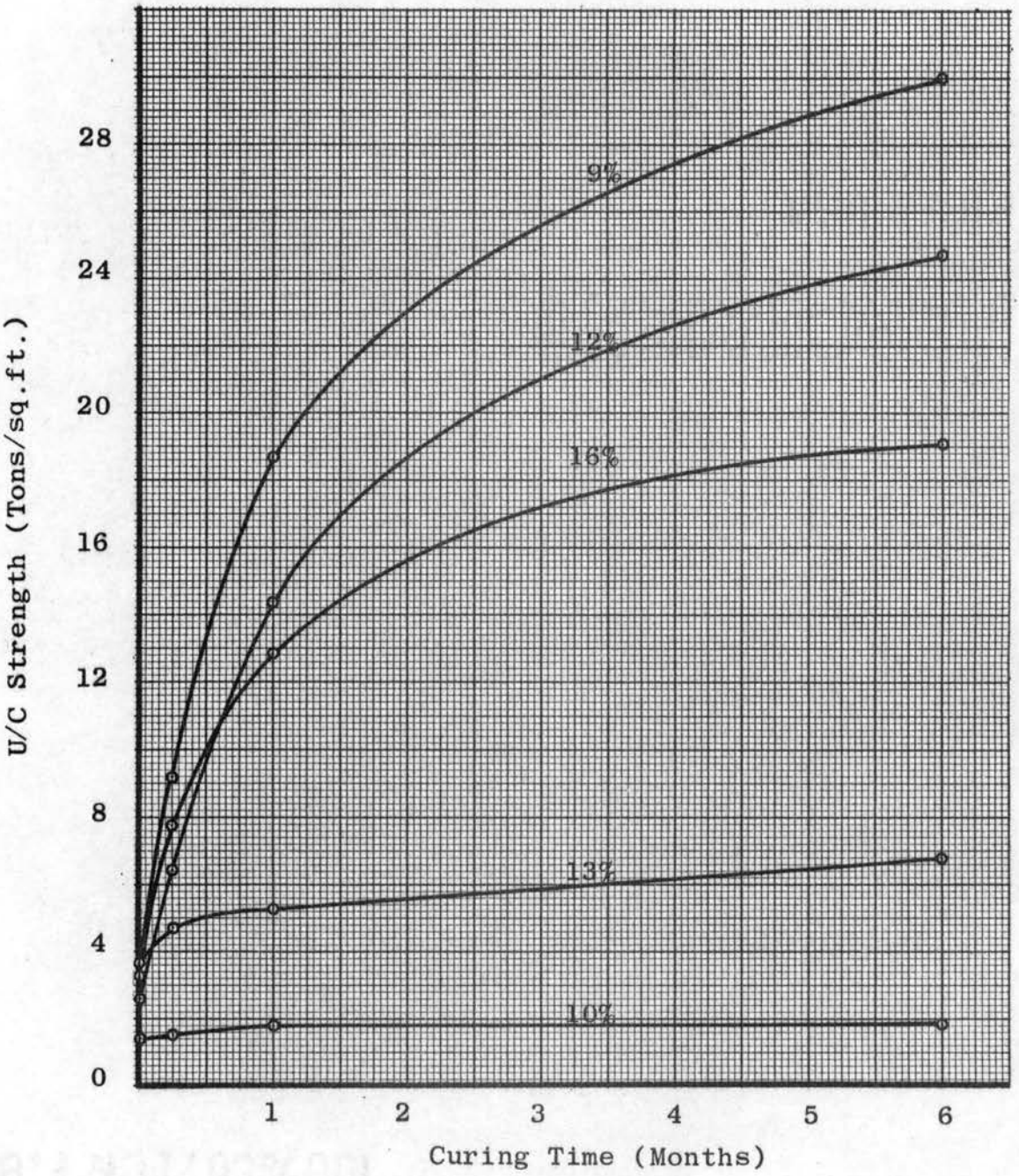

FIGURE 19

EFFECT OF CURING TIME
ON THE
STRENGTH OF PERMIAN CLAY AND LIME

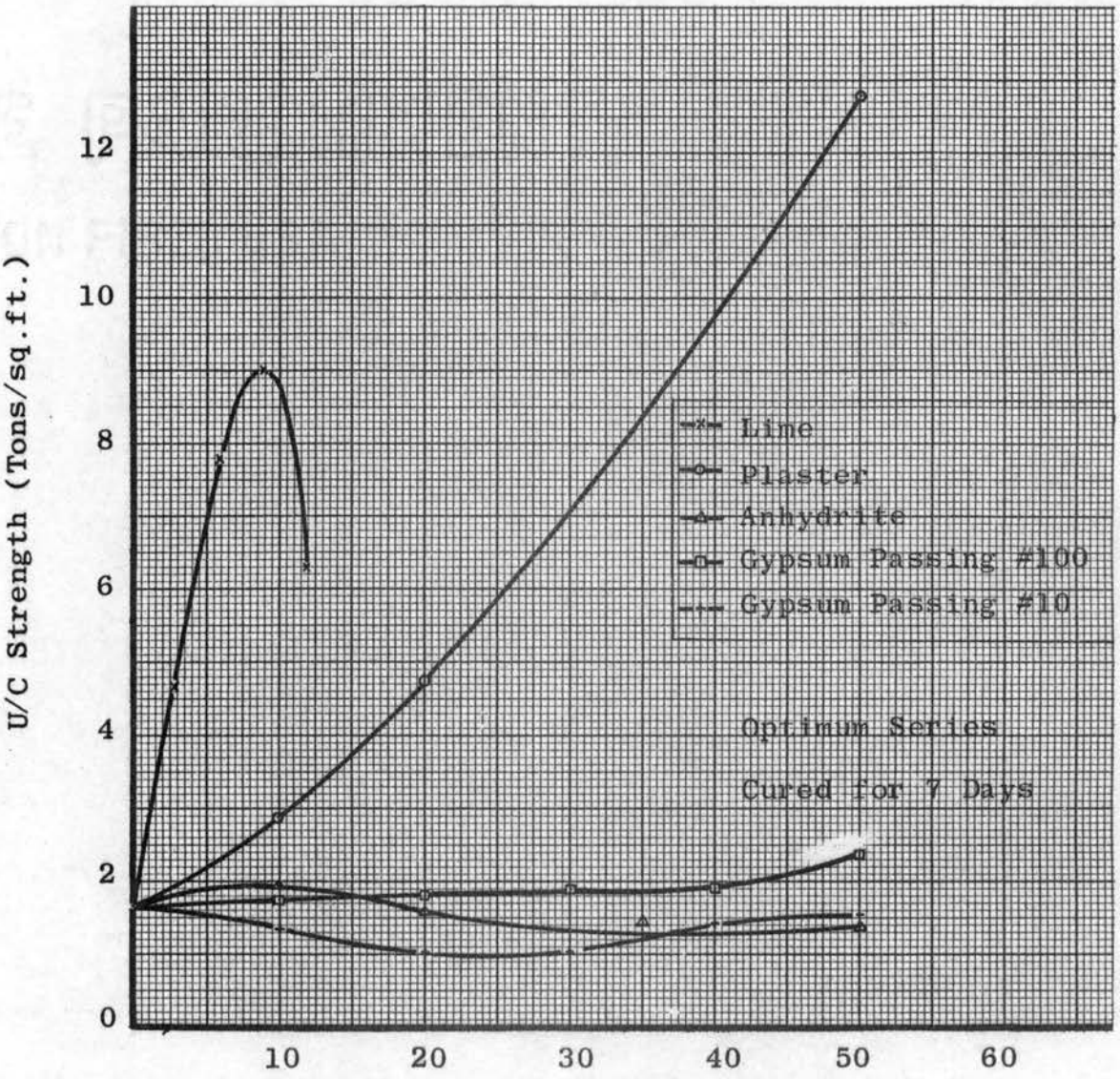

FIGURE 20

EFFECT OF VARIOUS ADMIXTURES
ON THE UNCONFINED COMPRESSIVE
STRENGTH OF PERMIAN CLAY

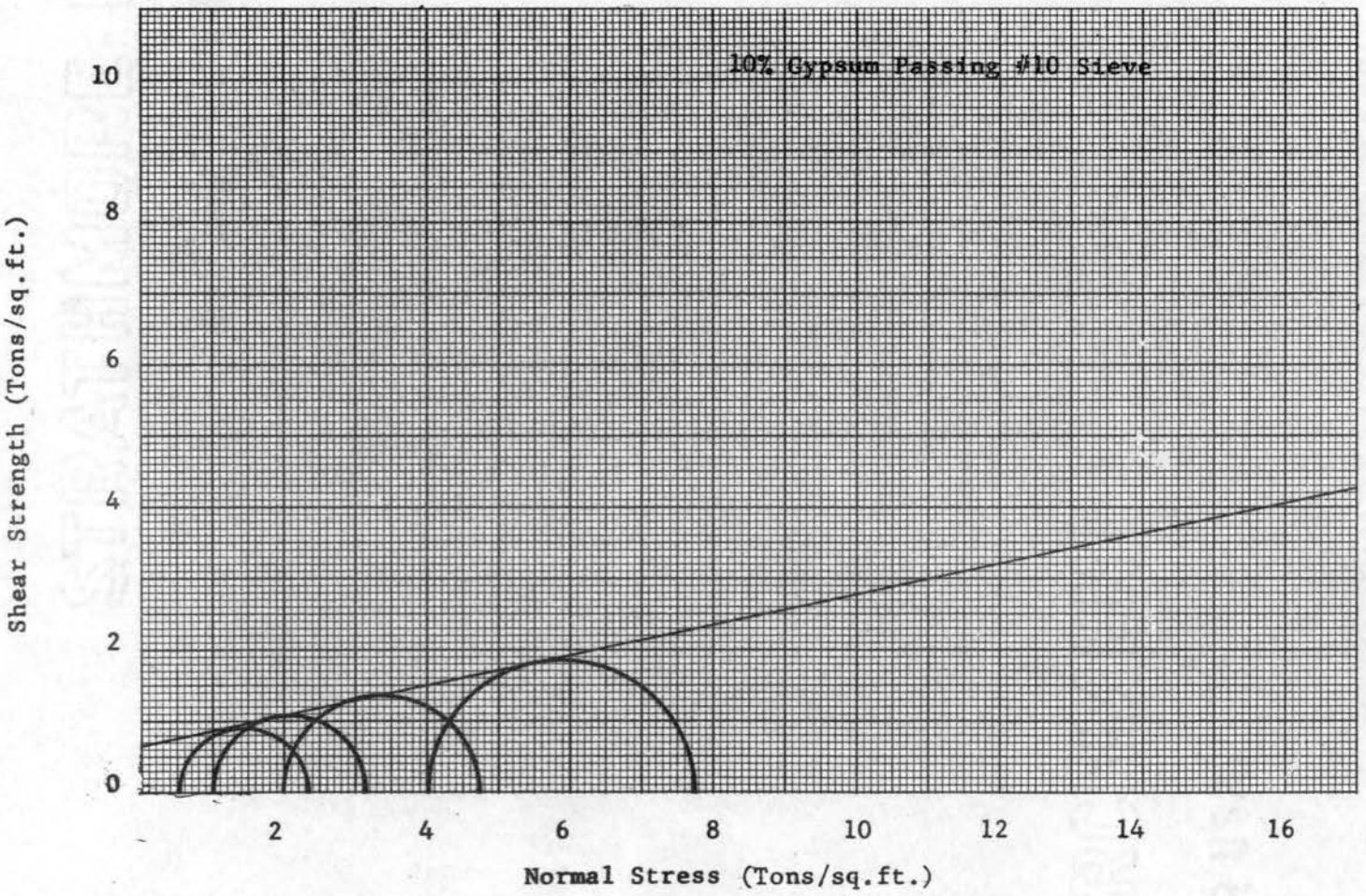

FIGURE 21

EFFECT OF GYPSUM ON THE SHEAR STRENGTH OF PERMIAN CLAY AS DETERMINED BY THE TRIAXIAL TEST

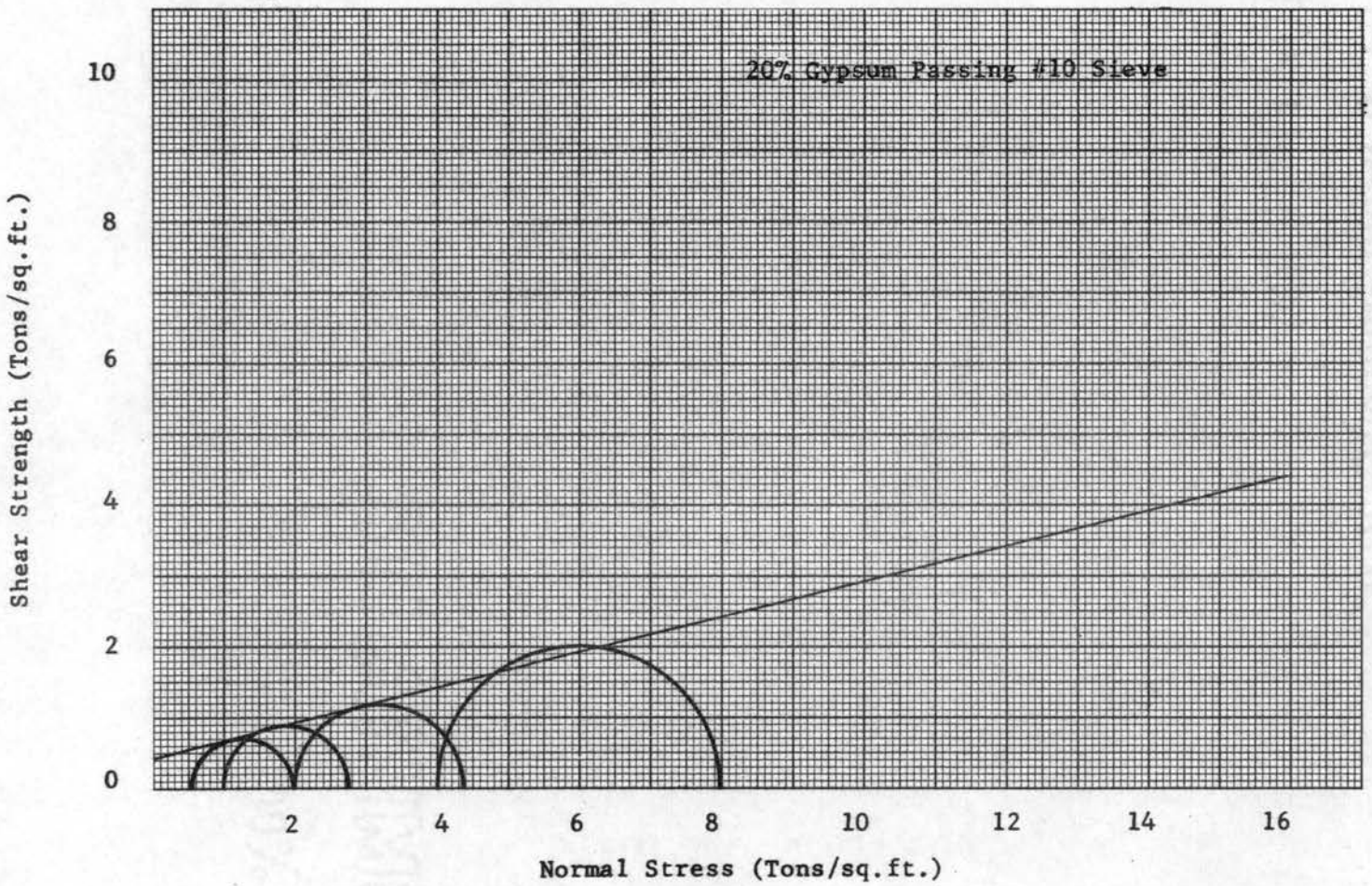

FIGURE 22

EFFECT OF GYPSUM ON THE SHEAR STRENGTH OF PERMIAN CLAY AS DETERMINED BY THE TRIAXIAL TEST

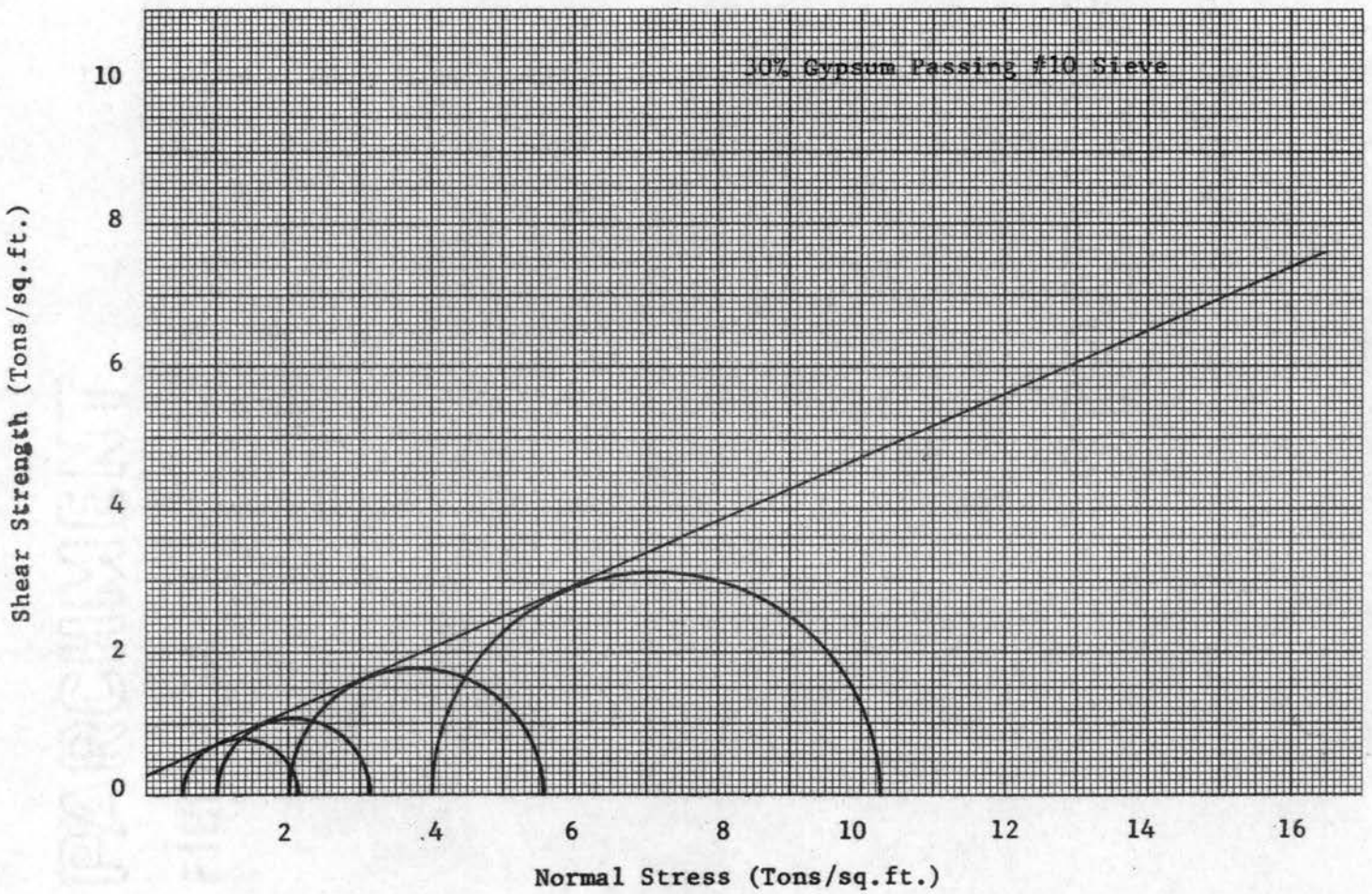

FIGURE 23

EFFECT OF GYPSUM ON THE SHEAR STRENGTH OF PERMIAN CLAY AS DETERMINED BY THE TRIAXIAL TEST

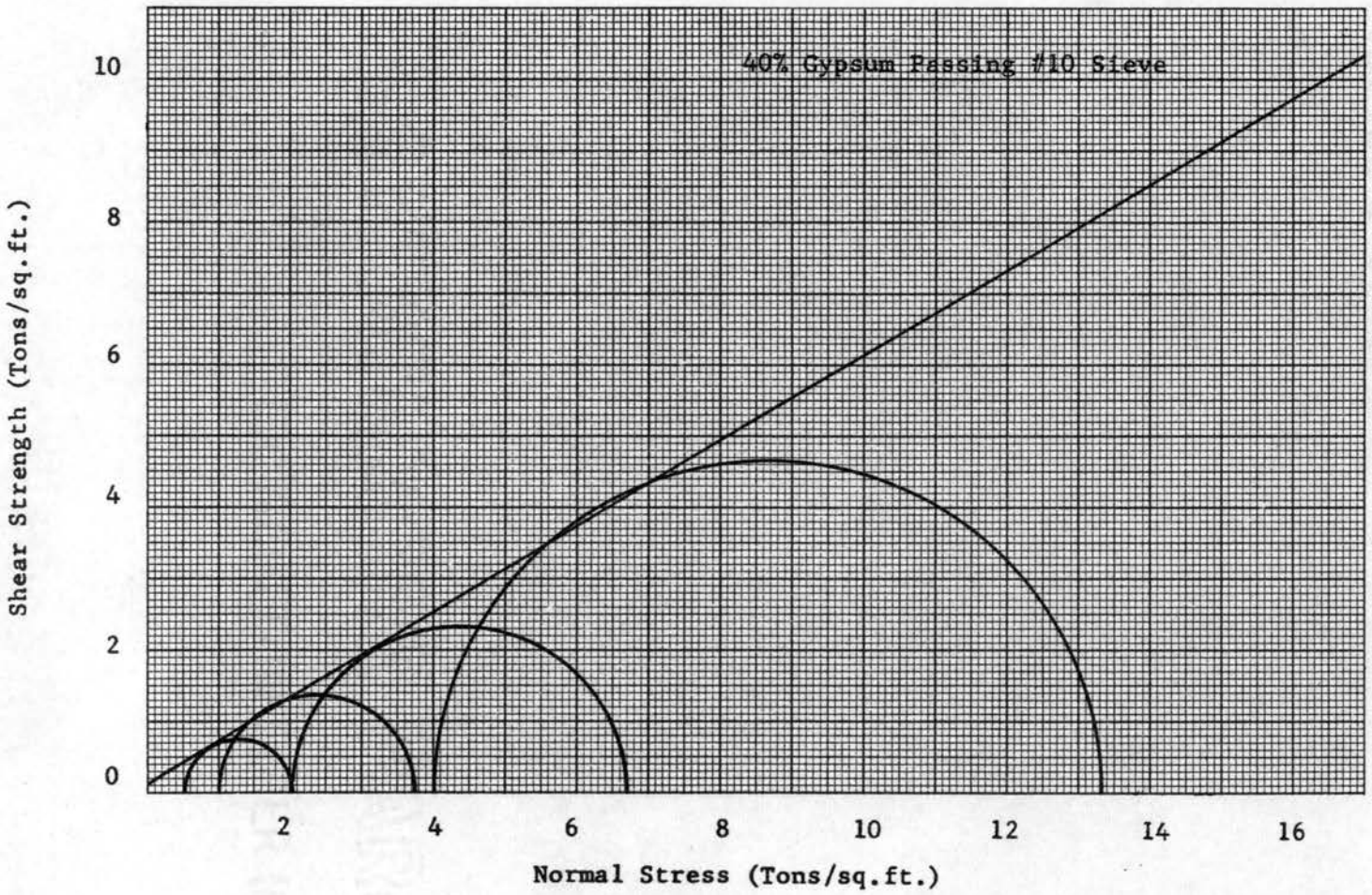

FIGURE 24

EFFECT OF GYPSUM ON THE SHEAR STRENGTH OF PERMIAN CLAY AS DETERMINED BY THE TRIAXIAL TEST

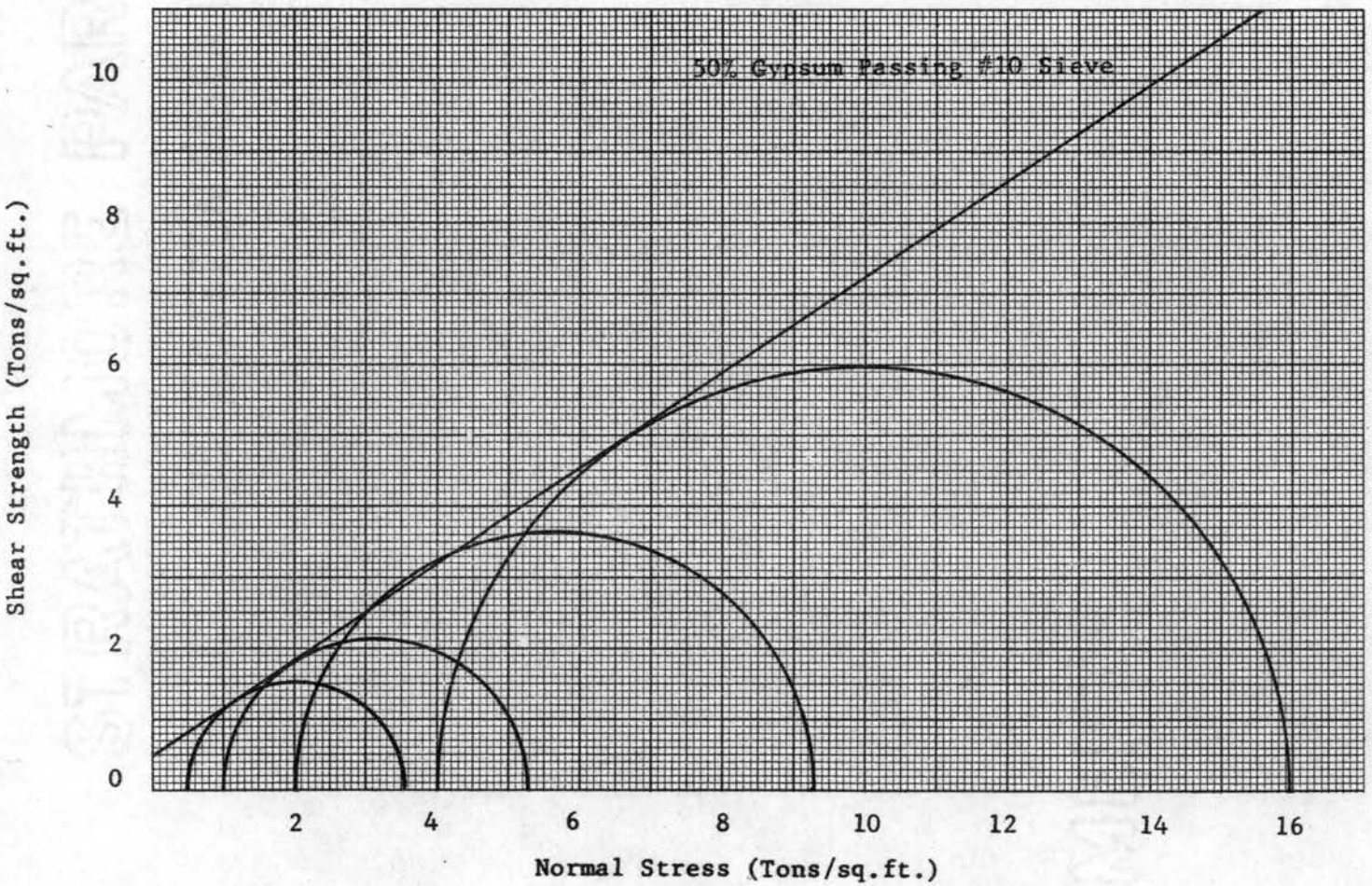

FIGURE 25

EFFECT OF GYPSUM ON THE SHEAR STRENGTH OF PERMIAN CLAY AS DETERMINED BY THE TRIAXIAL TEST

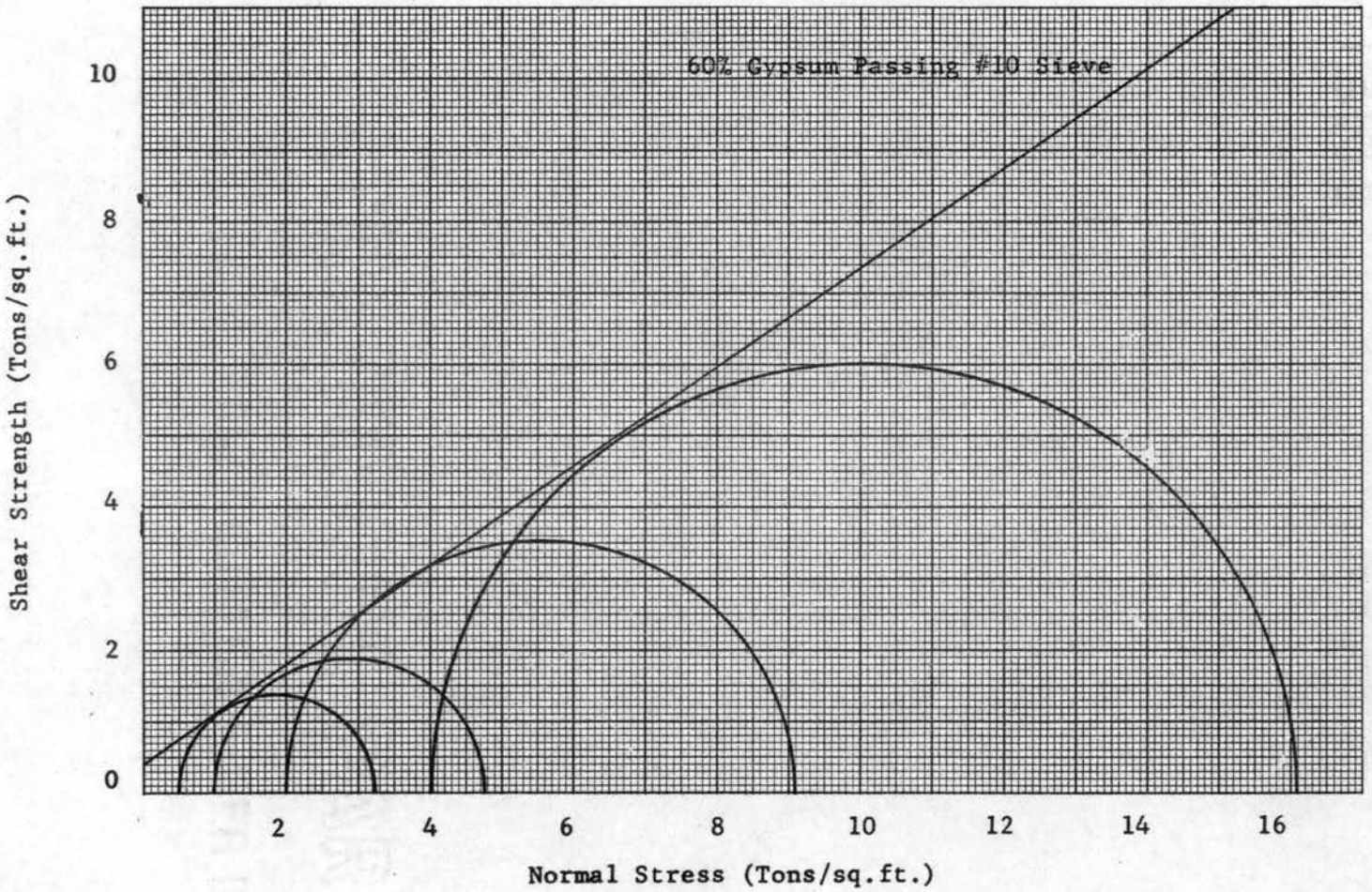

FIGURE 26

EFFECT OF GYPSUM ON THE SHEAR STRENGTH OF PERMIAN CLAY AS DETERMINED BY THE TRIAXIAL TEST

PLATE NO. I

UNCONFINED COMPRESSION TEST APPARATUS

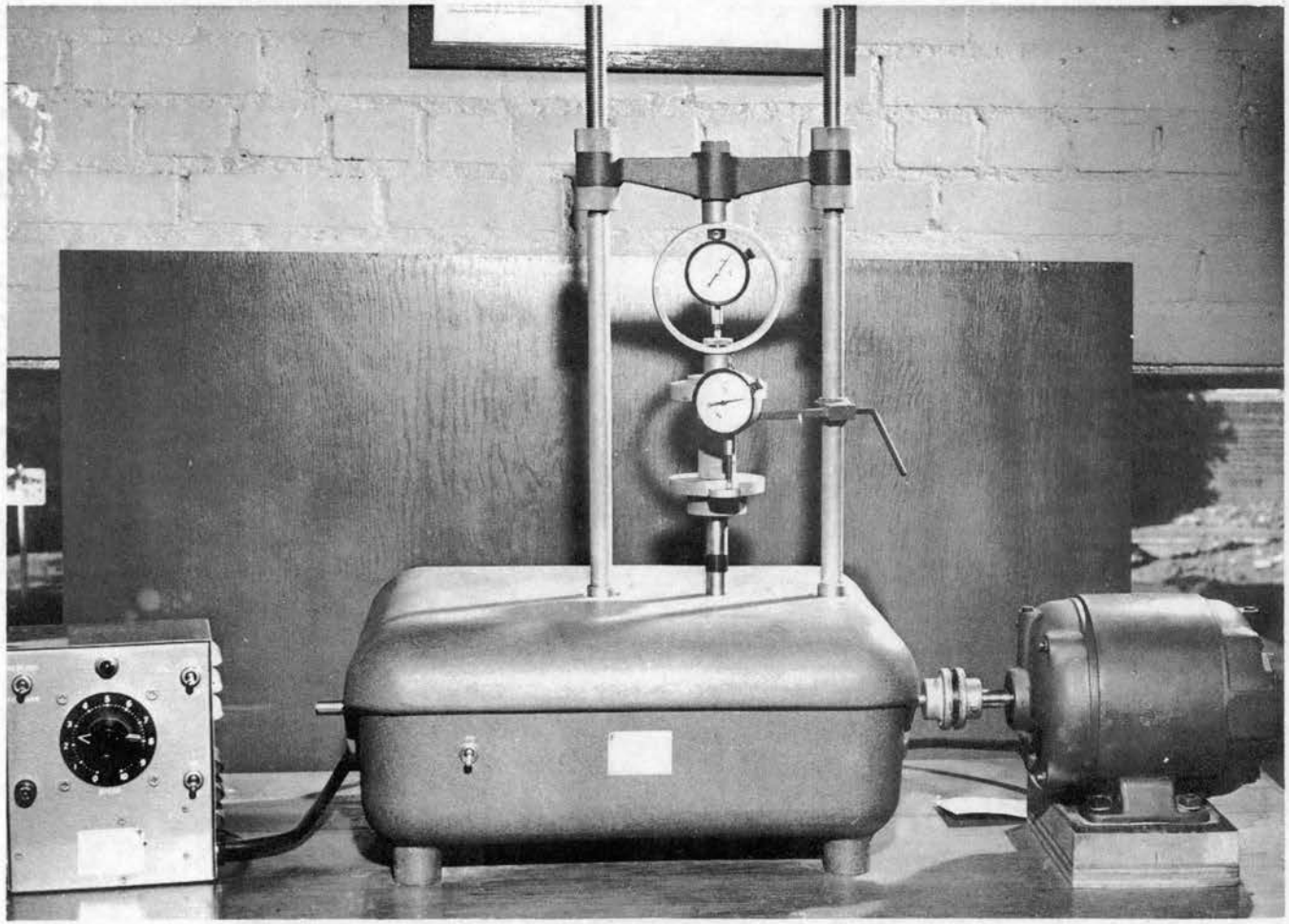

PLATE NO. 2

APPARATUS FOR TRIAXIAL STRENGTH TESTS

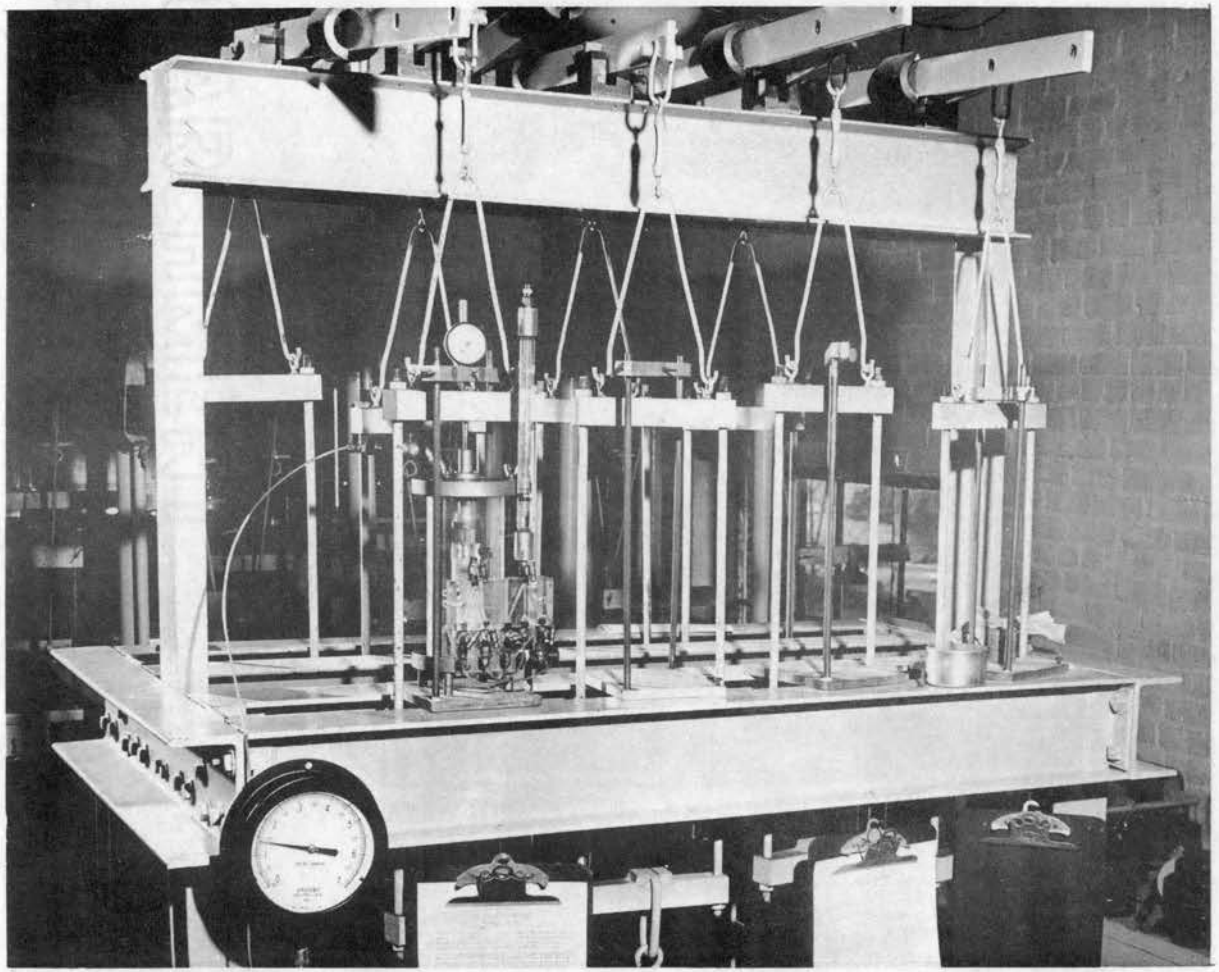

PLATE NO.3

PVC METERS USED FOR SWELLING TESTS

VITA

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